METROLOGY FOR HIGHLY PARALLEL MANUFACTURING

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

Overview

MetHPM will result in 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. MetHPM will deliver targeted inline metrology tools for defect detection, substrate tracking and critical dimension measurement for efficient diagnostic activity and process feedback, including the measurement traceability and standards for such metrology tools.

Need

HPM use is growing rapidly. Expanding markets now need more efficient and more traceable manufacturing processes. Existing markets demand 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 cannot solve the conflicts between metre scale substrate size, high throughput, and sub micrometre scale 3D feature dimensions. Crucially, metrology is 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 will add light management, antimicrobial, and security functionality to macroscopic surfaces. Similar growth is 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 requires MetHPM to develop widely-applicable metrology solutions. Very high speed 3D feature inspection will be 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 will lead to the development of smarter inspection metrology for HPM by tackling key gaps in metrology capabilities. The specific technical objectives of the project are 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 includes 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 will advance the state of the art in four areas:

Sensor systems. Current inline surface inspection methods cannot achieve the required resolution performance whilst simultaneously supporting HPM's large substrates and fast production throughputs. MetHPM will deliver: 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 will enable industry to overlay to better than 10 µm through novel sub-1 µm accuracy lateral substrate position metrology. Complementary methods to monitor alignment and overlay accuracy of metre scale substrates, including camera-based registration control and direct substrate embossing of alignment fiducials, will be created. These will be supported by pre-normative concepts for the verification of overlay accuracy, and user-friendly flexible substrate models.

Surface parameters for intelligent inline quality control. This project will tackle the 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 will increase the efficiency of surface-function correlation at HPM pilot lines and it will demonstrate direct exploitation of correlation data for real-time automated process feedback.

Traceability and standardisation. Standardisation for HPM applications is still in its infancy (e.g. IEC TC119 for printed electronics initiated in 2012). This project will improve traceability and standardisation by developing: new HPM-compatible inline transfer artefacts and calibration procedures; pre-normative proposals for substrate overlay metrology and surface-function correlation; and by developing new stakeholder-matched training: this will include the preparation of guidance and relevant test cases to promote the uptake of standardisation and of the cost-saving metrology tools developed in the project.

Results

The MetHPM consortium has already advanced the instrumentation state of the art for each of the key dimensional metrology challenges identified in the proposal. The workplan covers truly novel techniques and methods adapted and introduced to HPM markets.

Sensor systems. MetHPM will develop and demonstrate a toolbox of surface metrology techniques ready for application in hybrid inline inspection modules for HPM. This will balance both novel, true high-dynamic range concepts and the much smarter, faster and traceable use of 3D surface topography sensors, scattering-based technologies and machine vision. 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 an industrial consortium partner. 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. In another example, a hybrid 2D/3D inspection platform has been developed to: demonstrate new, faster metrology approaches for e.g. printed and large-area electronics; 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. 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 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.

Metrology for substrate handling. Multiple techniques have been developed to provide the substrate positioning feedback that is needed for precision overlay and reprocessing in production R2R systems. For example, partners 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. Other tools such as camera-based registration control, gravure-cylinder registration mark metrology, and pilot-line-verified overlay accuracy detection concepts have been delivered. In addition, the consortium is preparing guidance for printing facility users on how substrate choices influence achievable printing accuracy – based on the modelling of quasi-static and dynamic deformation of large flexible substrates. Finally, pre-normative concepts are being developed for the verification of overlay accuracy following the development of general concepts.

Surface parameters for intelligent inline quality control. This project is delivering new practical tools and techniques 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. One test case considers quality control of screen-printed electrodes on silicon PV wafers. Significant correlation between section-based calculated resistance from 3D topography measurements and local resistance measurements of fingers have been determined on test structures. The most useful quantitative descriptors of topography, geometry and electronic properties have been defined to enable the feedback pathways. Good practice guidance will be a key project output, building on industrial case studies and involving typical laboratory instruments.

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 are a project focus. Enhancements are underway to surface topography and application-specific standardisation (e.g. proposals for substrate overlay metrology and surface-function correlation), and will be complemented by HPM-compatible inline transfer artefacts and calibration procedures. 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 are being prepared to promote the uptake of standardisation and the cost-saving metrology tools developed in this project.

Stakeholder engagement. A variety of HPM-based industrial case studies will run through the project and these will allow the consortium to demonstrate a selection of the developed measurement technologies. This will allow us to communicate the value and function of the new metrology and to encourage the take-up of the technology and measurement infrastructure. The consortium welcomes further examples from industry.

Impact

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.

MetHPM is designed to directly address the most challenging metrology barriers to creating product value in HPM today. The project will, therefore, benefit 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 are raising awareness of the MetHPM objectives and results at key industry events e.g. 7th PrintoCent Industry Cluster meeting (Oulu, June 2015), 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 recently showcased at the International Metrology Congress (Paris, September 2017), along with new calibration artefacts. More generally, 8 papers have been published in international journals (listed in the next section), with a number of others under preparation.

Impact on relevant standards.
The priority is to collate and rationalise relevant specification standards from the contributing industries (topography, machine vision, print, semiconductor fabrication, application-focussed). The consortium is targeting application-specific technical committees such as IEC TC119, in which the first MetHPM-relevant IEC TC119 standardisation activities have already begun. A new ISO 25178-linked areal calibration standard, to be supplied with guidance and training, is now in production to encourage take-up of existing standardisation. The consortium will introduce fast, inline instrument classes to ISO 25178 development.

Impact on industrial and other user communities
This project will equip stakeholders with new metrology tools which will significantly reduce costs and wastage and which will increase product value. 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. Demonstration of new inline surface metrology methods – for example adapted scatterometry – 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. Improved substrate tracking metrology and models will immediately be offered for use by the stakeholder partners for comparative testing of new alignment concepts. For example, project outputs relating to fast grating critical-dimensional measurement have already been modified and exploited for sub-micrometre repeatability substrate tracking at Cranfield University’s R2R platform. 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 the calibration business case, MetHPM will highlight test cases on efficient, feature-parameter-based surface/function correlation determination – followed by inline process control where appropriate – emphasising the calculated commercial gain. 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.

Impact on the metrological and scientific communities
MetHPM aims 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). MetHPM will guide capability transfer towards R2R production, complementing current materials-science driven ‘bottom-up’ innovation. Leading by example, the consortium have already 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) to emphasise the multiscale industrial challenges in HPM to the dimensional metrology community.

List of publications

Madsen MH *et al.* 2016 Alignment free characterization of 2D gratings *Applied Optics* **55** 317-322

Madsen MH and Hansen P-E 2016 Scatterometry—fast and robust measurements of nano-textured surfaces *Surf. Topogr.: Metrol. Prop.* **4** 023003

Madsen JS *et al.* 2016 Measuring multiple nano-textured areas simultaneously with imaging scatterometry *Proc. euspen 16th Int. Conf., Nottingham, UK, 31 May – 3 June*

Jones CW *et al.* 2016 A universal substrate sample fixture for efficient multi-instrument inspection of large, flexible substrates, with absolute position registration support *Proc. euspen 16th Int. Conf., Nottingham, UK, 31 May – 3 June*

Madsen MH *et al.* 2016 Comparison of Scatterometry, Imaging Scatterometry, AFM and Confocal Microscopy *Proc. 4M/IWMF, Kgs. Lyngby, DK, 13–15 September*

Madsen MH *et al.* 2016 User Friendly Scatterometry *Proc. EOSAM, Berlin, DE, September*

El Gawhary O 2017 Helmholtz Natural Modes: the universal and discrete spatial fabric of electromagnetic wavefields, *New J. Phys.* **19** 013021

Kouko J *et al.* 2017 Measurement of Thermoplastic Properties of Packaging Materials *Proc. IAPRI 28th Symposium on Packaging, Lausanne, CH, 9 - 12 May*

<table>
<tr><td colspan="2">Project start date and duration:</td><td>1 May 2015, 36 months</td></tr>
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Partner 1 NPL, United Kingdom
Partner 2 DFM, Denmark
Partner 3 INRIM, Italy
Partner 4 VSL, the Netherlands
Partner 5 VTT, Finland</td><td>External Funded Partners:
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