INTEGRATED METROLOGY
10-YEAR ROADMAP FOR ADVANCED MANUFACTURING

APRIL 2020

CONTENTS

ACRONYMS

AFRC - Advanced Forming Research Centre

AM – Additive Manufacturing

AMRC – Advanced Manufacturing Research Centre

CMM – Coordinate Measuring Machine

CNC – Computer Numerical Control

CPI – Centre for Process Innovation

EPSRC – Engineering and Physical Science Research Council

HVM Catapult– High Value Manufacturing Catapult

MMT – Manufacturing Metrology Team

MTC – Manufacturing Technology Centre

MTRL – Manufacturing Technology Readiness Level

NAMRC – Nuclear Advanced Manufacturing Research Centre

NCC – National Composite Centre

NDT – Non-Destructive Testing

NPL – National Physical Laboratory

PBF – Powder Bed Fusion

PI – Principal Investigator

WMG – Warwick Manufacturing Group

INTRODUCTION

For advanced economies to remain globally competitive, they must transition toward high-value manufacturing as we move towards "Industry 4.0", sometimes referred to as the 4th Industrial Revolution [ISGF]. Future products will be typified by high levels of innovation, increased complexity and, especially, high levels of precision and quality. Successful firms will be capable of rapidly adapting their physical and intellectual infrastructures to exploit changes in technology as manufacturing becomes faster, more digital, more responsive to changing global markets and closer to customers. To support the manufacture of advanced products and to increase the degree of automation in manufacturing, increased reliance will be placed on metrology [NMS]; the key to control. Metrology allows the digital signature of a product to be traced through the entire manufacturing process, allowing digital data to be traceable, trustworthy and effective. Whereas metrology has traditionally been carried out after manufacturing, the trend nowadays is for "integrated metrology" (see the Integrated metrology definitions section). The result of the measurement can be used to control the process and/or to inspect the quality of the product. The HVM Catapult is in a unique position in the UK to transition the research in integrated metrology from academia out into the industry – in this document, it is our primary goal to lay out a roadmap for the adoption of integrated metrology at the HVM Catapult sites, and in UK advanced manufacturing in general.

KEY AIM

The aim of this project was to carry out a roadmapping exercise that would pave the way for the development of a systematic approach to integrated measurement and control for advanced manufacturing systems, to identify and guide opportunities for commercialisation of early research, and to define necessary future research themes across the Manufacturing Technology Readiness Levels (MTRLs). This document is the primary output of a project jointly funded partly by the UK Engineering and Physical Sciences Research Council and the HVM Catapult. The purpose of this paper is to provide a thought piece for the wider metrology and manufacturing communities.

INTEGRATED METROLOGY DEFINITIONS

The following definitions and their meanings were used during this exercise to categorise the various terms used within integrated metrology ("integrated" refers to measurements during manufacturing, e.g. during a cutting or laser additive process). Figure 1 shows the typical positioning of a defined type of measurement with respect to the manufacturing process and Figure 2 shows the relationship between the various integrated metrology terms. Note that these terms are slightly different from those that have been suggested in a 2019 CIRP

Keynote paper [Gao et al. 2019], but they are closer to terms used in UK industry. The terms are currently not standardised, so there is still time for debate. The separate terms in Figure 1 and Figure 2 are defined in the following sections.

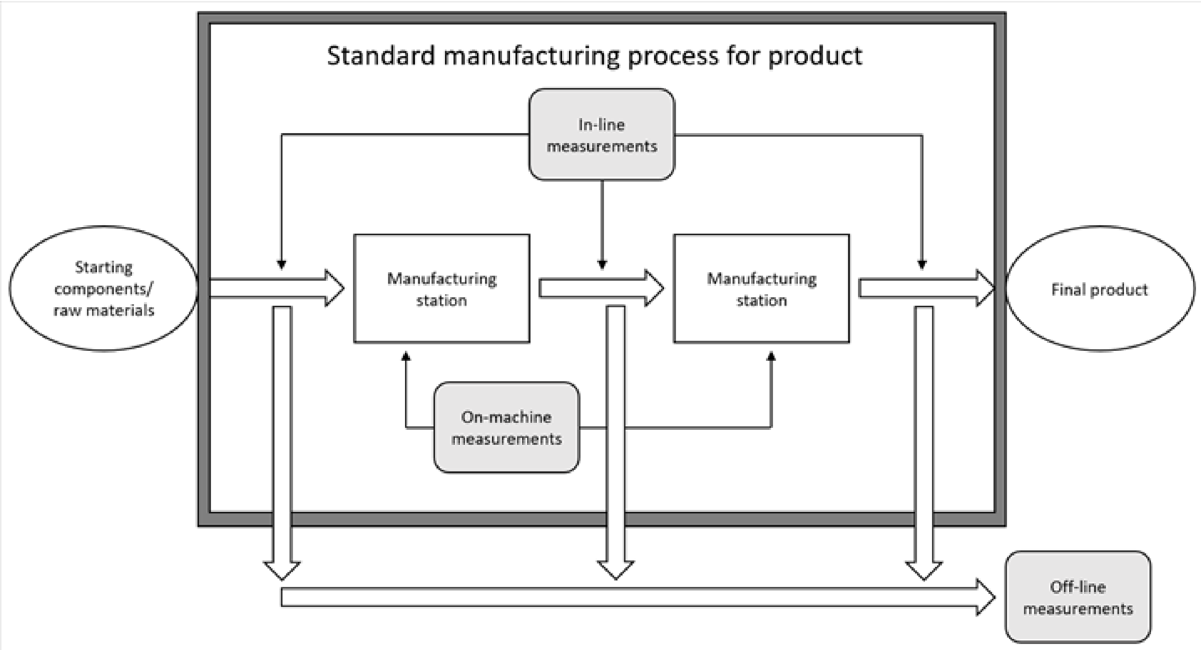


FIGURE 1. FLOW DIAGRAM OF A STANDARD MANUFACTURING PROCESS, VISUALLY DEMONSTRATING WHERE EACH TYPE OF INTEGRATED MEASUREMENT TAKES PLACE.

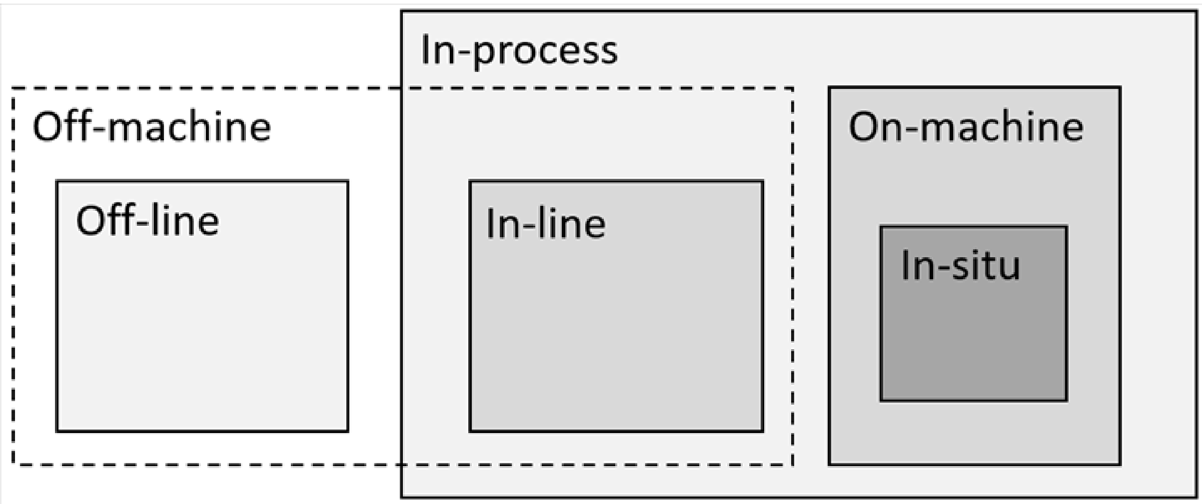


FIGURE 2. A DEMONSTRATION OF HOW THE DIFFERENT METROLOGICAL TERMS RELATE TO EACH OTHER IN MOST CIRCUMSTANCES. THESE TERMS CAN HAVE SOME OVERLAP, FOR EXAMPLE, BOTH IN-LINE AND OFF-LINE MEASUREMENTS MAY BE SITUATED ON-MACHINE, IN SOME CASES.

In-process metrology

In-process metrology is any measurement taken that can be used to predict or detect issues during the manufacturing process. In-process measurements must be synchronised with the manufacturing process so that the process can be monitored. All in-process measurements must be integrated into the standard production process for the part being manufactured, so that they are time sensitive. If a measurement is being performed during the manufacturing process, but is not being utilised for process monitoring and control, then that measurement is not in-process and is instead defined under off-line due to the purpose of the measurement.

Off-line metrology

Off-line metrology is any measurement that is not in-process. Off-line measurements are not synchronised with the standard manufacturing process and, therefore, cannot be used for process monitoring. A component measured off-line can be returned later to the process line, but this measurement does not cause a time delay in the process of other components and is not an essential part of the production line. Off-line measurements will often be conducted outside of the manufacturing environment, either on a measurement station in the factory that is separate from the standard process line (sometimes referred to as at-line) or in a laboratory. Off-line measurements can also be, in some cases, on-machine, but never in-process, due to there not being an intent for process control with the data.

In-line metrology

In-line metrology is a form of in-process measurement that occurs right before, right after or between manufacturing stations. In-line measurements are taken on separate measurement systems along the standard production line where manufacturing is not occurring. These measurements are often taken off-machine, but in some situations may be on-machine if a single machine consists of several manufacturing stations. In-line measurements are regular and must be taken before the next stage of the process can continue, either for each individual part before it moves to the following manufacturing station, or as a sample from a batch. An in-line measurement must be part of the product's standard manufacturing process and be used for process monitoring and control.

On-machine metrology

On-machine metrology is a form of measurement that is used to record data on a station during manufacturing. On-machine measurements can determine any variable that provides information about the process. In many scenarios, on-machine measurements are in-process but can be off-line if the data is not being utilised for process monitoring and control. (In contrast, off-machine would describe any measurement that is not taken on the manufacturing station.)

In-situ metrology

In-situ metrology is a form of on-machine measurement that primarily records data directly from the location where the manufacturing phenomenon is occurring. In-situ measurements are used to monitor how the equipment is interacting with the work piece. This can be through measuring at the point of interaction directly or through measurement of the work piece shortly after the phenomenon has passed, before the station's task is complete.

ROADMAP CONTRIBUTORS

The Principal Investigator (PI) was Professor Richard Leach from the Manufacturing Metrology Team (MMT) at the University of Nottingham. Other contributors from MMT were Patrick Bointon, Andrew Dickins, Lewis Newton, Adam Thompson and Luke Todhunter.

The roadmap was established through collaboration with the UK's HVM Catapult. At an early stage, it was decided not to include the Centre for Process Innovation due to their focus on the processing sector (as opposed to the advanced manufacturing sector) and due to the limited resources available to develop the roadmap. The HVM Catapult sites and key contacts were as follows:

- Advanced Forming Research Centre

  University of Strathclyde
  85 Inchinnan Drive, Inchinnan
  Renfrewshire PA4 9LJ
  Key contact: Daniel McMahon

- Advanced Manufacturing Research Centre

  University of Sheffield
  Advanced Manufacturing Park
  Wallis Way, Catcliffe
  Rotherham S60 5TZ
  Key contact: Richard James

- Nuclear Advanced Manufacturing Research Centre

  University of Sheffield
  Advanced Manufacturing Park, Brunel Way
  Rotherham S60 5WG
  Key contact: Simon Cavill

- Manufacturing Technology Centre

  Ansty Park
  Coventry CV7 9JU
  Key contact: David Ross-Pinnock

- National Composites Centre

  Bristol and Bath Science Park, Emersons Green
  Bristol BS16 7FS

Key contact: Ashley Moran

- Warwick Manufacturing Group

  International Manufacturing Centre, University of Warwick
  Coventry CV4 7AL
  Key contact: Alex Attridge

METMAP METHODOLOGY

To develop the roadmap, a number of tasks were undertaken, the results of which are summarised in this document. These tasks were as follows.

Task 1 Data-gathering at HVM Catapult sites

The aim of this task was to systematically gather the key data for a roadmap in integrated metrology across the HVM Catapult. At the start of the MetMap process, the PI became (and continues to be active on the new Assurance Group) an active member of the HVM Catapult Metrology Forum; taking guidance from the members who also include representatives from the National Physical Laboratory (NPL), the EPSRC Future Metrology Hub and the Institute of Measurement and Control. Existing post-process metrology roadmapping data formed the starting block for this task. Each HVM Catapult was visited to carry out an extensive inventory of existing integrated metrology and to capture future requirements, as well as understand barriers to those requirements and to identify key future R&D programmes. Planned interviews with key staff members were conducted using pre-determined questions. The outputs from this task are summarised in the Primary integrated metrology capabilities within HVM Catapult Section. The visits took place on the following dates:

- NAMRC – 28 May 2019
- MTC – 10 June 2019
- AFRC – 20 June 2019
- AMRC – 30 July 2019
- NCC – 11 September 2019
- WMG – 4 October 2019

Task 2 UK-focused conferences at HVM Catapult facilities

Two UK-focused conferences were hosted at HVM Catapult sites. The aims of these conferences were to present and promote key findings and establish any additional critical requirements from UK industrial users and manufacturers. The events engaged others from outside the HVM Catapult and targeted UK SMEs. The conferences included keynotes, state-of-the-art reviews, oral papers and an open forum. Participants were requested to fill out the surveys for Task 3. “Integrated Metrology for Precision Manufacturing” was held at the AMRC on 22 to 23 January 2019 and welcomed 63 attendees. “Integrated Metrology for Additive Manufacturing” was held at the MTC on 17 July 2019, welcoming 33 attendees. Full agendas for each conference can be found in Appendix A.

Task 3 On-line survey

To understand the landscape of integrated metrology in the UK advanced manufacturing industry (addressing data not captured in Task 1), a survey was conducted to capture the current state of the art and industrial requirements for integrated metrology to support and enhance UK manufacturing, plus provide input into the HVM Catapult roadmap. The survey was made available online from 23 November 2018 to 1 August 2019, advertised to relevant partners and conference attendees, and received twenty-six responses. The results from the survey are presented and discussed in the Key survey results Section.

Task 4 Final roadmap and recommendations

A final MetMap roadmap has been produced that presents the results from Tasks 1 to 3, including an implementation plan with recommendations for the next phase of commercialisation and R&D in academia, the HVM Catapult and UK industry. All HVM Catapult partners were invited to comment on a draft of the roadmap and a presentation was given at the HVM Catapult Metrology Forum. The roadmapping is highly relevant to the activity of the HVM Catapult due to its underpinning and enabling nature. This roadmap identifies and guides opportunities and gaps for both commercial exploitation and further research within integrated metrology. This roadmap is presented in the 10-year MetMap roadmap for the future of integrated metrology in advanced manufacturing section.

THE CURRENT STATE OF THE ART OF INTEGRATED METROLOGY CAPABILITIES WITHIN HVM CATAPULT SITES AND INDUSTRY

STATE-OF-THE-ART REVIEW OF INTEGRATED METROLOGY

As outlined in the Made Smarter Review [Maier 2017] and UK Measurement Strategy [NMS], UK industry must increase its productivity. One way this is being addressed in manufacturing industries is through the adoption of digital manufacturing, by which all aspects of manufacturing from the supply chain through to machining, assembly and after care are modelled and simulated so that changes can be made before costly production processes take place. This approach (dubbed Industry 4.0) requires the creation, manipulation and sharing of large amounts of data. Many companies understand the need for these data-rich processes, but do not understand how to initiate them, what data to capture, how to establish confidence in such data, how best to use it or what is available for adoption. This applies across many high-technology sectors, including aerospace, automotive, medical instrumentation and precision optics. Moreover, the adoption of digital technology in manufacturing processes is currently hindered by lack of efficiency and confidence in data that is captured within those processes. Confidence in data is the key enabler for adoption of the Industry 4.0 methodologies. Through traceability, metrology is one of the pillars for demonstrating confidence in data, without which, industry suffers from unnecessary waste, inefficient processes and increased costs for quality. The enhancement in data capture afforded by adopting integrated metrology would enable right-first-time manufacture, reduce waste and scrap, and facilitate effective business decisions. Integrated metrology will enable manufacturers to depend on the accuracy of the data and information derived, and the validity of decisions made by humans and machines.

Digital manufacturing allows bespoke products to be produced in more efficient, sustainable, agile and cost-effective ways. This allows products to be improved in terms of functionality – they can be enhanced and customised to match the design function. Better products can have a huge effect on the wider UK priorities (outlined in the Eight Great Technologies [8GT] and Industrial Strategy Challenge Fund [ISCF]). Examples touch upon almost all areas, including enhanced systems for transport (terrestrial and space); food production and agriculture; pharmaceuticals, medicine and medical devices; advanced materials; and energy production and storage. All these technology areas require functionally enhanced products and can benefit from the data-driven processes required to make integrated metrology a reality. Manufacturing is the route to enhanced products, that are, in turn, the route to enhanced human activities, ultimately helping us make the UK world leading in terms of growth, sustainability, health and social well-being.

There are been several recent reviews of the technology for integrated metrology [Gao et al. 2019, Leach et al. 2019, Li et al. 2019, Syam et al. 2019]. The summary points from these reviews are briefly discussed here.

Integrated metrology plays an important role for precision manufacturing in a number of tasks [Gao et al. 2019]. The first task is initial alignment and/or positioning of a workpiece on a machine tool [Lei and Zheng 2017, Smith 2016, Doytchinov et al. 2019, DeFischer and Ross 2019]. Secondly, the most straightforward task of integrated metrology is to replace the conventional post-manufacturing inspection of the workpiece made on an off-machine or stand-alone surface measuring instrument. The integrated results can also be employed for the task of compensation machining [Jiang et al. 2018, Du and Xi 2019], and that of process and machine tool diagnosis [Karner et al. 2019, Hill et al. 2019, Jimenez-Cortadi et al. 2020]. Each of the tasks has common and special requirements for both the measurement system and the data analysis/feedback process.

There are many commercial (or close to commercial) sensors that can be employed for integrated metrology, but there still remain a number of barriers that need to be addressed before they can be fully integrated into digital manufacturing processes [Gao et al. 2019]. These issues can be split into two categories [Syam et al. 2019]. 1. Dynamic spatial range – do the sensors have sufficient resolution and range? This will be highly dependent on the process, e.g. hunting for microscale defects over automotive panel whilst simultaneously measuring the form error of the panel. 2. Temporal range – are the sensors fast enough so that they do not have a detrimental effect on the throughput of the process? Another significant issue with the adoption of integrated metrology is the vast amount of data that can be produced with high-resolution fast sensing technologies, and the associated challenges of handling big data. However, these data-rich issues can be opportunities if advanced data handling, analysis and learning methods can be developed and employed [Razvi et al. 2019]. These issues are ideal for machine learning, which is only now being utilised for measurement applications, to enhance the capability and performance of instruments, e.g. understand surface orientations [Stavroulakis and Leach 2016], automatically segment 3D point clouds [Monti et al. 2017], infer surface information from missing data using a priori information [Senin and Leach 2018] and automatically segment objects, especially for machine vision applications [LeCun et al. 2015].

Integrated metrology for AM, and in particular on-machine metrology, i.e., measurement while the part is being built, is one of the hottest topics currently being tackled by the manufacturing community (see reviews by [Leach et al. 2019, Grasso and Colosimo 2017, Everton et al. 2016]). The appeal of integrated measurement for AM resides in being able to detect problems early during fabrication. This offers the potential opportunity to salvage defective parts via the implementation of corrective actions, or at least offering the chance to discard parts early, avoiding the waste of time and resources, which could be prohibitively high, especially for low volume, high value-added parts. The challenge of integrated metrology for AM pertains both to making sure the measurement is not disturbed by the process (taking into consideration temperature, random disturbances due to volatiles, etc.) and making sure the process itself is not disturbed by the measurement (least interaction possible, and least modifications possible to the process in order to accommodate the measurement systems). Integrated measurement may often be subjected to severe time constraints, depending on the physical phenomena that must be monitored. Some measurements may be performed once for each fabricated layer or for every few layers; others multiple times within each layer; others may be required to operate at much higher sampling frequencies, for example, to capture the dynamics of the melt pool. There are evidently significant challenges ahead, but also room for growth, for the measurement technologies and systems dedicated to integrated metrology for AM.

Establishment of traceability for integrated metrology is an essential task for the assurance of measurement reliability and a key issue for extending the applications of integrated metrology in to manufacturing industries [Gao et al. 2019, Leach et al. 2019, Mutilba et al. 2017, Mutilba et al. 2019]. Artefact-based calibration and traceability is a common way to achieve reliability [Carmignato et al. 2020], but future strategies need to be developed based on self-calibration [Gao et al. 2019, Papananias et al. 2019]. Data processing, including sampling strategy [Larsen et al. 2017, Lu et al. 2019], defect identification and handling [Tolle et al. 2019, Psarommatis et al. 2019, du Plessis et al. 2019, Leach et al. 2019], data acquisition and analysis, is another important part of integrated metrology; particularly for the feedback of measurement data for process control.

As one of the future trends in integrated metrology, continuous progress in sensor technologies is expected to improve the robustness and reduce the cost of integrated measuring instruments. More applications of integrated metrology are also expected in both precision and additive manufacturing industries. In the near future, integrated metrology has the potential to become an essential part of a manufacturing process as well as a common function on a machine tool. To realise this goal, comprehensive standardisation work on both hardware, such as the mountings, interfaces and controllers, and software, such as control codes for sensor output acquisition, error analysis, embedded calibration methods and automatic compensation tool path generation, is essential [Xiao et al. 2018, Maurya et al. 2019, Leach et al. 2019, Qin et al. 2019].

PRIMARY INTEGRATED METROLOGY CAPABILITIES WITHIN HVM CATAPULT

Visits were performed at six of the seven HVM Catapult sites alongside questionnaires in order to assess the capabilities present for integrated metrology. For clarity, common processes across the HVM Catapult sites are discussed individually in order to explain conventional metrological requirements and to highlight examples of current capabilities.

Machining

The process category of machining refers to the use of manual and CNC mills, drills and lathes or other conventional manufacturing methods. Such machine tools are common within all HVM Catapult, although their requirements for metrology differ. Measurements can either be taken with or during a tool change (often with specialised tool probes), or continuously monitored and either relate to the tool, the part or the machine. Some of the more common measurements are of temperature, position, spindle speed/acceleration and force/pressure on tool; with an aim to provide predictive maintenance for the machine tool. Some more advanced in-process metrology includes surface or dimensional measurements to ensure part quality and design specification.

Current capability for integrated metrology is varied across the HMV Catapult. At the AMRC, there is current capability for the retrofitting of legacy equipment with modern sensors to measure motor temperature, spindle speed/acceleration, and position – which are commonly already integrated in other HVM Catapult's modern machine tools and allow for predictive maintenance. The MTC has capability for smart drilling: using laser trackers to position robotics, thermocouples for temperature monitoring and post-drilling coordinate measuring machine (CMM) verification. For the modern systems at the AMRC, there are additional sensors, such as radar and optical probes, laser tool checkers and mounted calibration spheres, in addition to the integration with the central server (MSP server) for data storage with the capability for remote monitoring.

Welding (conventional and non-conventional)

Welding refers to processes that join materials together, typically metals, using the application of high temperatures. This does not include techniques that are classified as additive manufacturing but does include friction welding (the application of pressure on rotating surfaces to generate heat). Typically, visual inspection of weld quality is used during the process either optically or thermally, although these measurements need to consider the high temperatures involved in the process.

For automated welding, the NAMRC has the capability for mechanised arc welding with in-process measurement of distortion using laser triangulation, cameras for visual inspection, microphones for sound measurement, voltage/current measurement and laser line scanning in 2D – which is stacked to produce 3D data. Similarly, the WMG has the capability for 3D scanning in-line, which compares measurement data to CAD in order to adjust process parameters in-situ for their laser welding system. For friction welding, the current capabilities are the measurements of force, spindle speed and temperature with an example of this integrated at the AFRC.

Additive manufacturing

Additive manufacturing (AM) processes deposit material layer-upon-layer to fabricate a part. With various process categories able to produce different material components, the identified capabilities are for polymer AM and metal AM. With monitoring of process parameters and condition available on machine, additional measurements are commonly taken in between layer fabrication – requiring fast measurement and analysis speeds so as not to significantly slow down the overall process. A commonly identified aim for integrated metrology with AM is to monitor for defects within the build, however, considerations must be made with respect to the build mechanism.

For polymer AM, the common AM process technologies across the HMV Catapult are powder bed fusion (PBF), ink-jetting, binder-jetting and fused filament fabrication. For metal AM, the most common technology is PBF, with both laser and electron beam systems used. Ambient temperature is monitored for all AM systems. Capability is highly dependent on the specific system being used, and any advanced development is through project work at the HMV Catapult. Lower capability refers to use of the in-built sensors that can monitor the process, such as printer head temperature, vacuum condition, pre-heat temperatures and airflow within the system respective to the process and material. More advanced capability is found on metal PBF systems at the MTC who are developing capability to take measurements for the whole layer thermally and/or optically; other sensors might monitor the melt-pool as it scans to calculate thermal energy density, emissivity and specific wavelength emissions.

Forging/forming/pressing

These grouped processes use applied pressure/force and sometimes heat to deform material to a desired shape. As a result of the mechanism, pressure, force and temperature are common measurements taken to monitor these techniques which include forging, shear forming, flow forming, super plastic forming, hydroforming, hydraulic pressing, all used at the AFRC.

The automated forging system at the AFRC uses a fringe projection form measurement system for point tracking between tool changes as well as force, pressure and acceleration sensors. Increased capability is found on the radial forge with sensors for temperature, forces on each axis, electrical output, position of each hammer and pressure, which are used to control stop/start function without any capability for correction. Most forming processes monitor pressure and force with some specific processes, such as hydro-forming, also measuring clamping force, whilst for the super plastic forming system up to 300 parameters are collected every 0.01 s that check gas pressure, ram force and gas flow rates (to monitor leakage) – which is also feedback controlled. The hydraulic press has the capability to monitor die temperature, press positions, load and speed, all at a sample rate of 0.1 s to 1 s.

Composite manufacture

The NCC specialises in the production of composites, with most manufacturing equipment highly specialised and all found within a production line to allow for complete manufacture. Composites generally have unique measurement requirements, such as fibre angle, placement and layer thicknesses, as well as other requirements for form measurement and defect detection. Most systems for composite manufacture contain some inbuilt sensors, examples include the ovens/autoclaves, which monitor temperature, pressure and time, and the hand layup process that measures vacuum level. Many systems to produce composite parts are automated and already integrate visual inspection to monitor the part produced.

The automated fibre deposition systems at the NCC employ technologies such as camera vision systems and laser triangulation line scanners to perform in-process measurement for material placement and fibre angle. The automated preform cell measures before, during and after manufacturing, using a laser line scanner to measure the height of the preform and a camera to monitor the ply alignment in-process. The overbraider, which weaves composite material around a circular axis, uses in-process laser scanning and high-resolution cameras to monitor the process, exporting information to custom software.

Battery manufacture

At the WMG, the Energy Innovation Centre is the national facility for battery research. The processes involve the mixing of powders into slurries, processing with a binder, coating onto rollers which are then used to produce cells. Along this process are varying metrology systems for monitoring. The desired measurement of the battery manufacturing process is the porosity, which is currently inferred from measurement of mass and thickness.

Mixers are used to produce the battery materials which monitor speed, time and temperature on the process, with operator feedback control. The coating process is capable of pressure and speed measurement for the pump that feeds material to the coaters, with an ultrasonic sensor used in-process to measure the mass (thickness) of the coating (measured both wet and dry). The final process before assembly is a calendaring process which is capable of defect detection using camera vision technology.

Further capabilities

Robotics and automation capabilities

Most HMV Catapult sites currently apply some form of automation, with many systems using robotics to present parts to different manufacturing processes within a manufacturing cell. Robotics are also used currently to either move the part to a measurement instrument, or the instrument around the part. For feedback control, whilst some systems already use automated methods that use sensor data to change manufacturing input parameters, it is still common for systems to use sensors but rely on manual feedback control.

Data management capabilities

For data management, the state of the art is a centralised server system at the NAMRC, which collects data from the various sensors and systems and collates them into one place – from which remote monitoring can be performed. There are other systems at the HMV Catapult sites to store data on site, however, requirements to store data for set periods of time create limitations in data storage and access.

Digital twinning is another capability, using a digital replica of a component that follows the part through the manufacturing process digitally, based on the application of predictive modelling and simulation – which can be further improved with information from the manufacturing process.

Metrology and NDT capabilities

Metrology labs are common at all HMV Catapult, providing capability for post-process dimensional metrology for both form and surface measurements using contact and optical systems. There are also automated inspection cells at many HMV Catapult sites, with examples such as the auto-inspection cell at the MTC, which has machine vision cameras and interchangeable sensors, and the composite integrity verification cell at the NCC, which is a fast and automated NDT cell that uses ultrasound, thermography and shearography to verify composite parts.

KEY SURVEY RESULTS

In addition to engagement with HMV Catapult, part of the MetMap project was to produce an online survey that was made available to key partners and attendees of the two UK-based conferences. This survey was created as a method to probe the greater manufacturing industry to obtain key information about the current state of integrated metrology. The survey obtained a total of twenty-six responses from five countries including the UK, USA and China, with 81% of responses coming from small to medium sized business (see Figure 3), giving key insight into the current capabilities of smaller manufacturing enterprises.

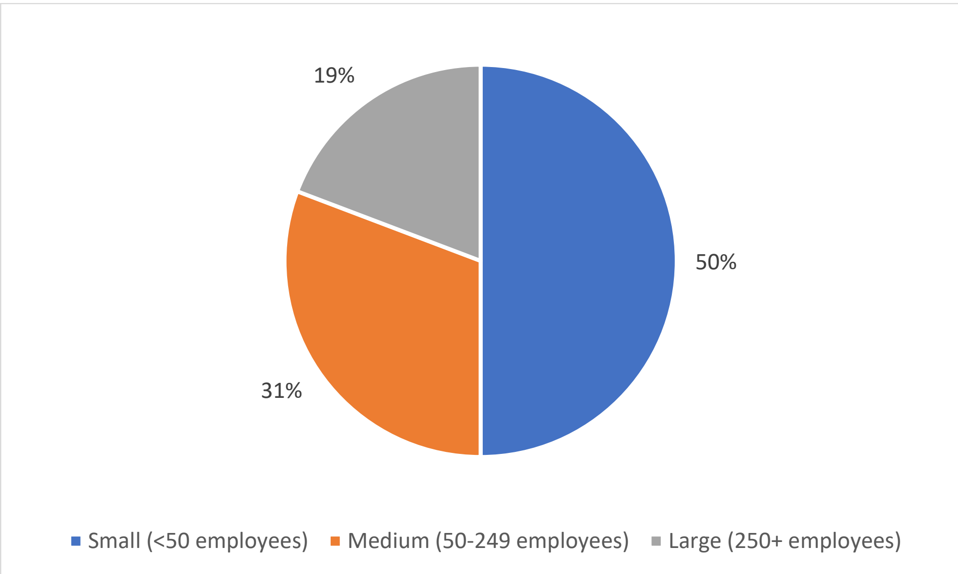


FIGURE 3. COMPANY SIZE OF SURVEY PARTICIPANTS.

Figure 4 shows the integrated metrology techniques used by the survey participants. The results show contact techniques are the most popular, such as probe and stylus instruments, with 85% of participants claiming use within their integrated metrology practices. Optical instruments are surprisingly very close behind, with 77% adoption, suggesting most participants use a combination of optical and contact techniques. Measurements with a focus on build environment, such as thermal and humidity sensors, are less popular.

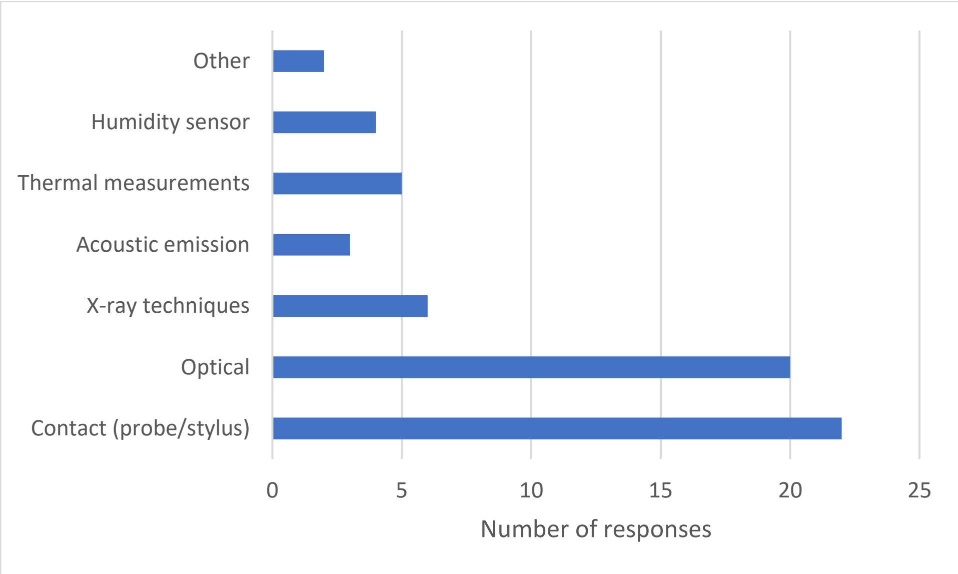


FIGURE 4. METROLOGY TECHNIQUES USED BY SURVEY PARTICIPANTS.

Survey participants were also asked which forms of integrated metrology were currently in use, with the results given in Figure 5. These results show a high degree of integrated metrology, with 65% of participants performing some form of on-machine measurement. However, only 54% of responses noted the use of in-process measurements, suggesting that some of those on-machine measurements were performed off-line and were not utilised for process monitoring or control. In-situ measurements are often the most challenging to perform, depending on the manufacturing process, yet were performed by 38% of participants in the survey. This is a substantial response count, given the difficulty of the measurement category, and highlights the importance of measuring tool-part interactions in industry as a method of process control.

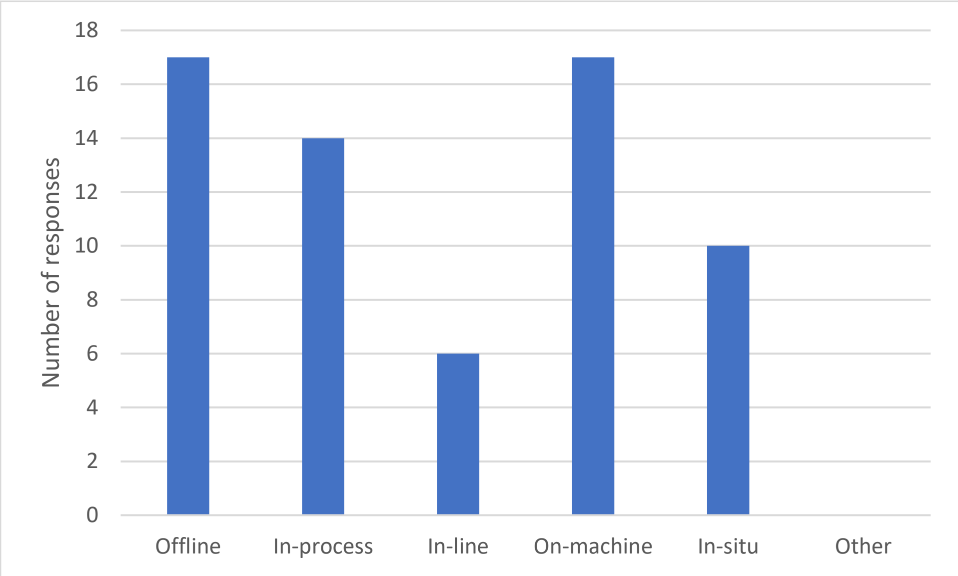


FIGURE 5. FORMS OF INTEGRATED METROLOGY USED BY SURVEY PARTICIPANTS.

IDENTIFIABLE AIMS AND NEEDS FOR THE FUTURE OF INTEGRATED METROLOGY

INTRODUCTION

The previous section of this report identified the current capabilities of HVM Catapult and industry regarding integrated metrology and the use of measurements performed during the manufacturing process as a means of ensuring quality control and operational performance. The same data-gathering opportunities, including questionnaires and face-to-face meetings, were also used to identify the future needs of the HVM Catapult and establish a vision for the future of integrated metrology for advanced manufacturing.

A series of seven key areas emerged as the primary focus for future goals in the field of integrated metrology to be achieved in the next ten years. These key fields cover a broad range of engineering disciplines and serve as the primary cornerstones upon which the integrated metrology roadmap is built. The following sections will address each of these areas, summarising their key components.

PROCESS INTEGRATION

Process integration involves the physically integration of measurement sensors and devices into the manufacturing process to better facilitate in-line measurements. This can include sensors fitted on-machine or even inside the machine to enable in-situ measurements.

The end goal for process integration would be full integration of measurement processes into the manufacturing line, and the reduction of time-consuming off-line measurements that require physical movement of the manufactured part to a dedicated measurement area, potentially pausing the manufacturing process. With the full integration of measurement capabilities in-line, crucial information about the part and/or tool can be obtained, even during operation. Measurement data can also be transferred immediately from the machine to a data processing station, avoiding the need to manually export the data from the measurement device using a physical transfer.

DATA ANALYSIS AND MANAGEMENT

Data analysis and management is another key area of development for the future of integrated metrology. As with any technology-based field, information processing is expected to increase exponentially with time. Many members of HVM Catapult and industry anticipate the use of more sensors over time with higher data speeds and higher information density. This leads to a crucial need to adequately manage and process this data. This includes the input, output and processing of all sensor and measurement data both to and from manufacturing machines.

The future of data management in this field is expected to be able to cope with large quantities of measurement and sensor data in real-time. This is likely performed with the use of a central processing hub; a network of connected computers that receive input from the sensors, perform the required analysis, and output the results either to feedback control units or machine users. Such an operation requires fast, efficient use of the vast quantities of measurement data, selectively identifying important information as required.

SENSOR DEVELOPMENT

Improvement in the speed, accuracy and information density of sensor technologies is an obvious requirement in the advancement of integrated metrology. The ability to obtain higher quality data at a faster rate is a common goal for many members of industry, regardless of the specific field. More specific to integrated metrology, however, is the ability to use sensors in environments that are not currently possible. Harsh environments, such as high temperatures, are common in manufacturing, particularly close to the tool/part interaction, and obtaining measurements at these locations can be difficult. Future developments of sensors are expected to address the current limitations of these harsh environments, enabling sensors to be used in-situ.

AUTOMATION AND ADAPTIVE CONTROL

One of the most popular categories that HVM Catapult and industry expect to see significant development is in the field of automation. Artificial intelligence (AI) has seen significant advancements in the last five to ten years, and it is anticipated that it will permeate almost all areas of engineering in the next ten years. The goal for the next ten years is to utilise AI and specifically machine learning to develop smart software that can facilitate the automation of decision-making processes to aid in the measurement and control of manufacturing. By intelligently monitoring in-process measurements and sensors, an AI-assisted system can adaptively control a manufacturing process, stopping a process when errors are detected, or even adjusting process parameters to retain consistency. Such an automated approach reduces the dependence on manual inspection and decision-making, speeding up the process and reducing the opportunity for human error.

DESIGN FOR METROLOGY/INSPECTION

To facilitate the integration of measurement devices and sensors, it is necessary to better design the manufacturing environment. By anticipating the need for integrated measurements, through the use of intelligently designed fixturing and machines, in-process measurements can be more easily performed.

Over the next 10 years, intelligent design for metrology is expected to be a major area of research and development. This includes features such as additional space and clearances incorporated within manufacturing environments for the specific inclusion of measurement devices and sensors. In addition, designing parts that include specific datum points has to ability to greatly improve the consistency of measurements performed.

TRACEABILITY, VERIFICATION AND VALIDATION

Traceability is an important aspect of integrated metrology to ensure trustworthy sensor and measurement outputs, particularly when running parallel machines or collaborating with external partners, is traceability. Proper calibration and validation of measurement equipment and techniques increases the quality of the information obtained, allowing more accurate process control to be achieved.

In the next 10 years, methods of traceability and calibration are anticipated to be incorporated into in-line and even on-machine measurement processes. This includes the use of calibration artefacts and self-calibration methods within the manufacturing area, including within the build area, to better calibrate for the specific setup and environment in which the equipment is operating. In addition, standardised procedures and methods are expected to be developed for integrated metrology-specific applications, such as defect detection and handling.

EDUCATION, COLLABORATION AND COMMUNICATION

Effective knowledge transfer is a crucial aspect of ensuring any current and future advancements in the field of integrated metrology are disseminated throughout the industry. Information gathering across the HVM Catapult and industry revealed the existence of current integrated metrology capabilities that are desired by others, including those at the same institution but in different departments. By encouraging the sharing of current techniques and ideas amongst departments and organisations, individuals' needs can be met even before the development of future products.

In the next 10 years, an increase in the education and communication between individual groups will improve the efficiency of the advancement of all other areas of integrated metrology. By developing the skills of all members of the field and establishing an awareness of the current state of the art, research and development resources can be more efficiently allocated to ensure novel advancements are made.

RESULTS OF AN INTERNATIONAL SURVEY

As introduced in the Key survey results section, an online survey was made available for members of industry to share their goals for the future of integrated metrology in advanced manufacturing.

Figure 6 shows the survey participants' future automation plans for the next 10 years. A substantial 77% of all participants expressed a desire to incorporate some (additional) form of automation into their current integrated metrology practices, with 35% wanting to fully automate all measurement systems. These significant numbers show the importance of AI and automation for the future of integrated metrology, and the need for substantial research and development into the future.

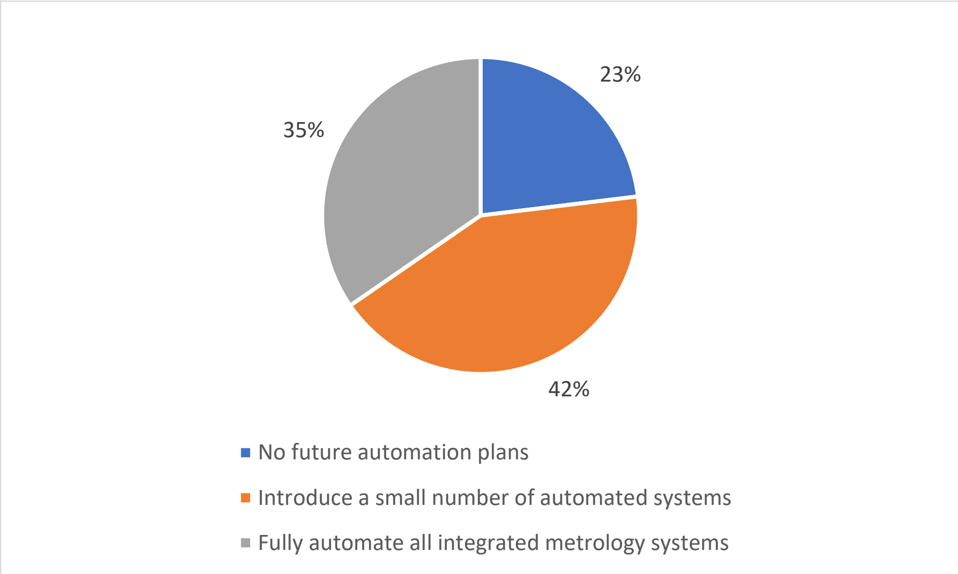


FIGURE 6. SURVEY PARTICIPANTS' PLANS FOR AUTOMATING METROLOGY TECHNIQUES IN THE NEXT 10 YEARS.

Figure 7 shows the current limiting factors for survey participants that are preventing them from incorporating integrated metrology techniques into their current manufacturing processes. Expectedly, the most popular barrier to entry is cost, with 58% of participants identifying it as a factor. Perhaps more surprisingly, is that the second most popular factor is lack of information and awareness of current integrated metrology techniques. This result solidifies the need for communication and education over the next 10 years, as discussed in the Education, collaboration and communication section, to ensure all members of industry are aware of the advancements in integrated metrology available to them.

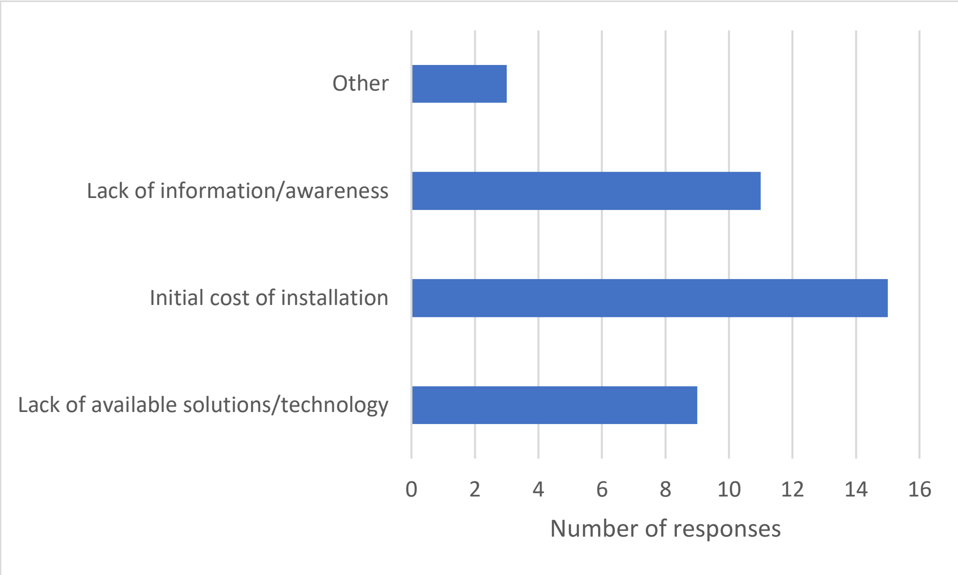


FIGURE 7. CURRENT LIMITING FACTORS PREVENTING SURVEY PARTICIPANTS FROM USING EXISTING INTEGRATED METROLOGY TECHNIQUES.

Figure 8. reveals the survey participants' priorities for research in development for integrated metrology over the next 10 years. The responses to this section are relatively evenly spread, with no one area taking clear priority over others. The most popular, with 27% of the vote, is the desire for a reduction in inspection time. Most forms of integrated metrology, besides in-situ measurements, require a pause in the manufacturing process in order to obtain the measurement. This has an associated cost penalty, as it can reduce the total number of manufacturing processes that can be performed in a day, and this delay is exaggerated for off-line and off-machine measurements. Process optimisation and component verification were equally popular, with process control only one vote behind. These three categories all call for an increase in the reliability and quality of the results obtained from integrated metrology systems. By improving the both the accuracy and the density of information that can be obtained from integrated measurements and sensors, components can be better verified, and processes can be better understood and, therefore, better controlled.

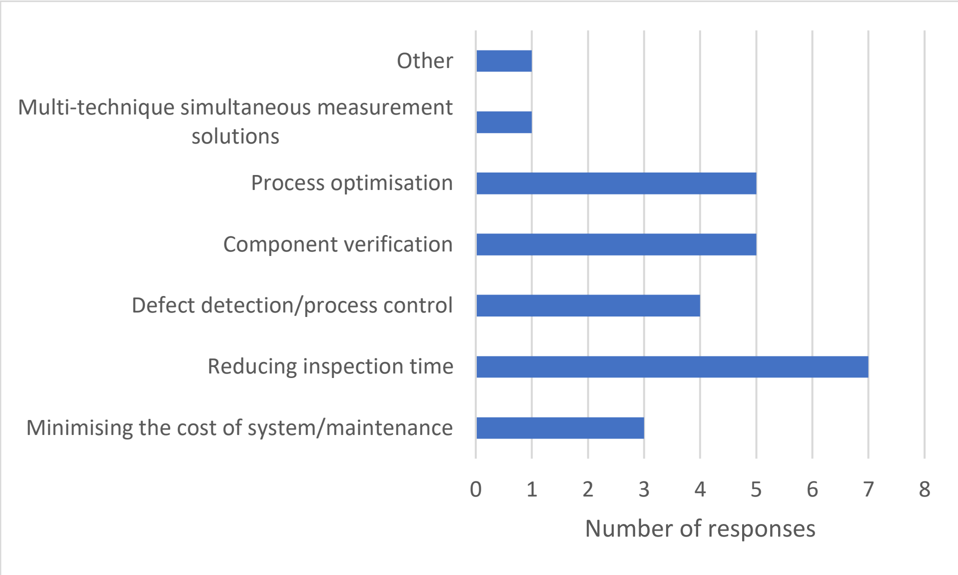


FIGURE 8. SURVEY PARTICIPANTS' PRIORITIES FOR THE FUTURE OF INTEGRATED METROLOGY.

PROPOSED ACTIVITIES TO ACHIEVE THE FUTURE AIMS OF INTEGRATED METROLOGY

INTRODUCTION

The Identifiable aims and needs for the future of integrated metrology section identified key categories that summarise the aims of HVM Catapult for integrated metrology over the next 10 years. These aims will enable a substantial increase in the quality, diversity and reachability of integrated metrology systems throughout industry. This section discusses the key research and development activities that must be performed over the course of the next 10 years in order to achieve these goals.

PROCESS INTEGRATION

The end goal for the next 10 years of process integration is to reach a point where a greater number of integrated metrology techniques are moved from off-line to in-process. To achieve this, research into the appropriate available measurement technologies must be performed for different manufacturing processes to identify what is needed to be measured, and which methods are best suited. From here, consideration into the environment the system will be subjected to must be addressed, for example by investigating temperature compensation methods for measurement systems in forging or machining environments. Novel methods of on-machine inspection may need to be developed, such as in-process optical measurement techniques suitable for placement within the build chamber for additive manufacturing. With the appropriate inspection method chosen, physical integration of the equipment into the manufacturing process must be performed, for example by embedding the sensors within the machine using secure, reliable and repeatable methods, or by facilitating the streamlined movement of a part into a location suitable for inspection. At this point, techniques can be developed that incorporate the newly integrated sensors and measurement systems into the manufacturing process, including the resulting captured data into process control operations.

DATA ANALYSIS AND MANAGEMENT

The aim for the next 10 years in the field of data analysis is to achieve real-time data capture and processing for multiple sensors and measurement devices simultaneously. To achieve this, research must be undertaken to develop a workflow that collates all relevant sensor and measurement data into one central processing unit. Using this, all analysis can be done in one system, streamlining the analysis process, allowing for a ubiquitous use of digital twinning and simplifying decision-making challenges. Alongside a centralised data workflow, standardised data formats must be developed that are compatible with many sensor types. This enables multiple measurement types to be collated together in one system easily. Developments in the efficient transfer of large quantities of real-time measurement data are also required, including appropriate compression techniques, to maximise the amount of unique information that can be transferred at a given data rate. Intelligent selection of critical sensor data is also required to maximise the value of stored information and minimise the cost of long-term data storage.

In addition to the need to *get* good data, any metrology solution embedded in a factory requires: (1) data confidence and (2) data trust. As the use of AI and deep learning start to remove the need for process improvement and optimisation in the manufacturing environment, the data being used to make decisions needs to have a high level of certainty to prevent the cost of quality significantly increasing due to the ineffectiveness of integrated metrology, and ultimately an inability to certify the process in a high value manufacturing environment. This will demand a new suite of codes, regulations and standards that need to be internationally realised to enable integrated metrology across the end to end supply chain.

SENSOR DEVELOPMENT

A primary area for research in the advancement of sensor technology and capability is the ability for sensors to withstand the harsh environments in some manufacturing processes. Robust sensors that can operate at very high temperatures need development and testing so that they can be integrated into machines and facilitate a new range of in-situ measurements. Sensor accuracy and speed can be improved through the development and use of the latest advancements in material and electrical technologies. By reducing the size of current sensors and measurement devices, integration into areas with limited space, such as within build chambers, becomes possible.

AUTOMATION AND ADAPTIVE CONTROL

As mentioned in the Automation and adaptive control section, automation is one of the major areas for the development of integrated metrology in the next 10 years, with a goal of creating fully-automated, decision-making systems. To achieve this vision, complete inter-machine communication is first required, to enable the transfer of data from manufacturing machine to a control unit, and vice versa. This aspect of research and development is linked the integration of a central processing unit and advances in streamlined dataflows mentioned in the Data analysis and management section. Next, machine learning techniques must be developed and utilised to train a computer system to identify critical manufacturing changes. This includes defect detection, and sensor/part relationships to facilitate process control. This training will need to be performed in tandem with a system expert to efficiently train the model. Once complete, decision-making algorithms can be developed that combine the trained system with real-time information from the sensors integrated into the manufacturing process. From here, control can be given to the system to adjust the parameters of the manufacturing process accordingly.

DESIGN FOR METROLOGY/INSPECTION

To achieve meaningful development in the future of advancing manufacturing, it is critical that metrology is intelligently considered and accounted for throughout the manufacturing process. Research needs to be undertaken to identify the most valuable and appropriate sensors and measurement techniques for each manufacturing environment and process. With this knowledge, bespoke considerations can be made that make integrated metrology into the manufacturing process much easier. This includes designing custom spaces inside the manufacturing area to accommodate measurement devices and sensors. Ease of data output should also be factored into manufacturing equipment design, so that real-time analysis can be achieved at separate, or even remote, computers and centralised processing units.

Thoughtful consideration of future inspection processes should also be incorporated into part fixturing, for example by allowing parts to be easily removed from machines and set up at a measurement station in a controlled manner, so that measurement techniques can be performed easily and repeatably, improving measurement quality and value.

TRACEABILITY, VERIFICATION AND VALIDATION

The integration of sensors and automated controls has limited value without proper sensor calibration techniques and established measurement traceability. Considerations during the design of manufacturing tools and equipment need to be applied to allow for the inclusion of calibration artefacts and techniques for any measurement devices and sensors that are anticipated to be included during the manufacturing process. A library of digital twin models should be developed by HVM Catapult that serve as references for SMEs to develop their own validation methods from an established starting point. Standardised, agreed upon definitions should also be produced for integrated metrology specific applications, such as defects, to better characterise the manufacturing process in a universally acceptable way, streamlining the development of automated process control and defect detection operations through machine learning.

Aside from the traceability issues specific to integrated metrology solutions, there is still a significant unsolved metrology challenge: optical instruments that produce point cloud data do not have a standardisation infrastructure and uncertainty statements are almost non-existence. There needs to be a significant push in this area. Another area that is not being addressed with enough gusto is the quantification of uncertainty when machine learning models are applied.

EDUCATION, COLLABORATION AND COMMUNICATION

To better encourage the widespread adoption of future advancements in integrated metrology in industry, regular knowledge transfer opportunities need to be created throughout the next 10 years - such as through dedicated conferences or steering meetings. Communication with the HVM Catapult has revealed desires for technology and practices that already exist within other departments, indicating that an improvement in communication is required.

Another round of in-depth discussions including all HVM Catapult sites, similar to that performed for the purpose of this roadmap, should be performed on a more regular basis. This can be disseminated not only to participants, but also the SMEs within industry, and will greatly improve the level of understanding regarding the current capabilities in integrated metrology available for adoption.

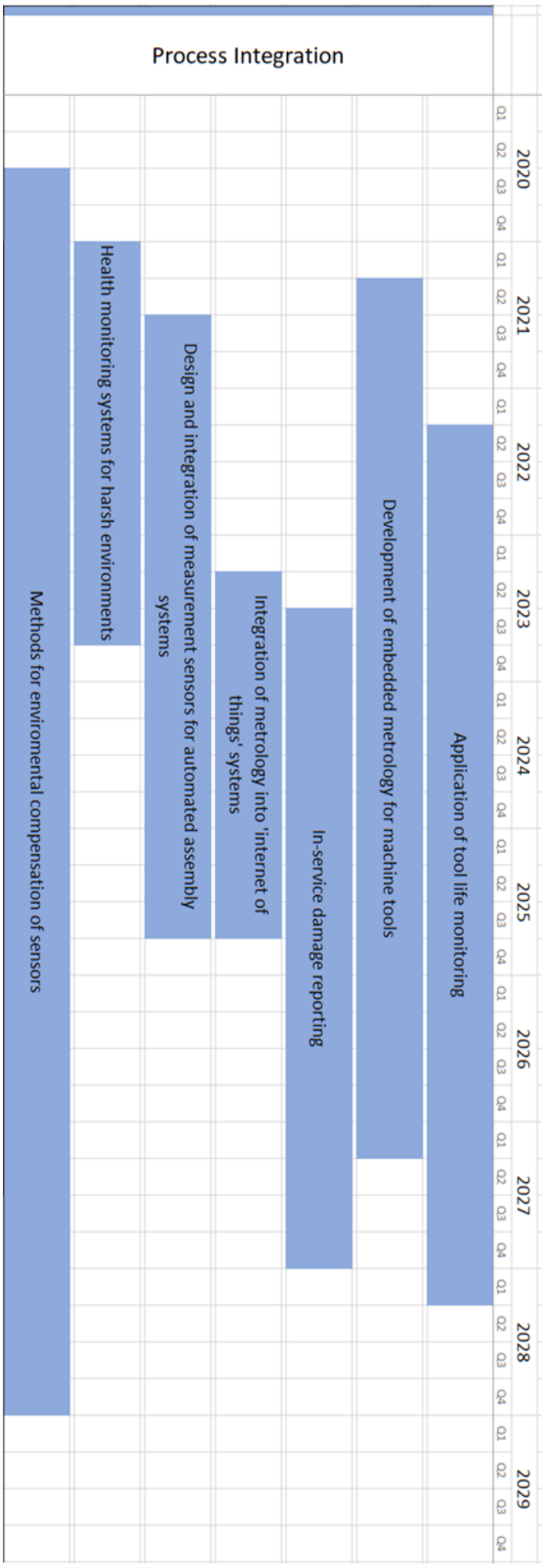
In addition, the use of expert users to develop standardised integrated metrology specific references, such as defect definitions or digital twin references, will enable the efficient transfer of expert knowledge to others in the field.

HVM Catapult with NPL should work with the engineering councils and institutes to build metrology into the UK-SPEC. Without this action, the fundamental knowledge required for the adoption of Industry 4.0 will not be available in the next generation of engineers.

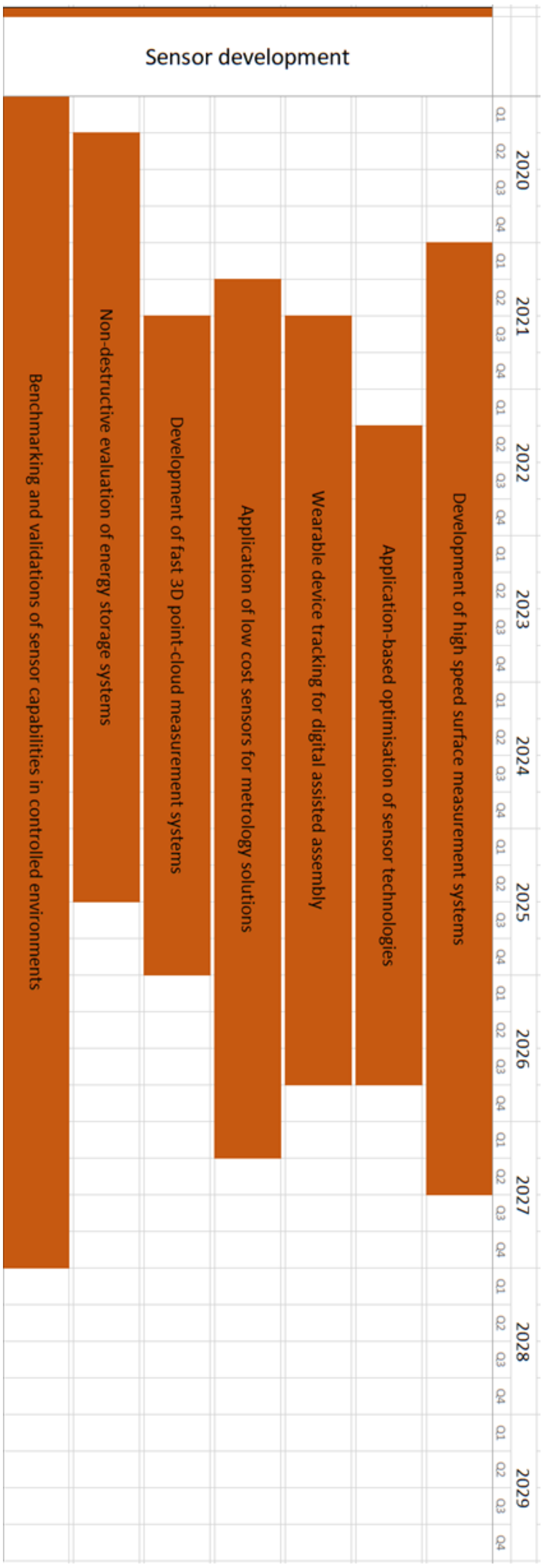
Although fundamental development of instruments, sensors and AI is being conducted in academia, it is industrial developers that are bringing these to market. HVM Catapult has a duty to engage with academia and industrial developers to ensure validity and the fitness for purpose of these technologies. HVM Catapult should take a role to de-risk the adoption by industry and be a source of knowledge as an independent advisor.

HVM CATAPULT with the NPL and standards bodies should drive an agenda on interoperability, veracity, validity and security of data. There is a current trend by industrial developers to lock customers into their products with proprietary formats, and this in the long term will be detrimental to UK manufacturers and limit the openness/connectivity of the supply chain.

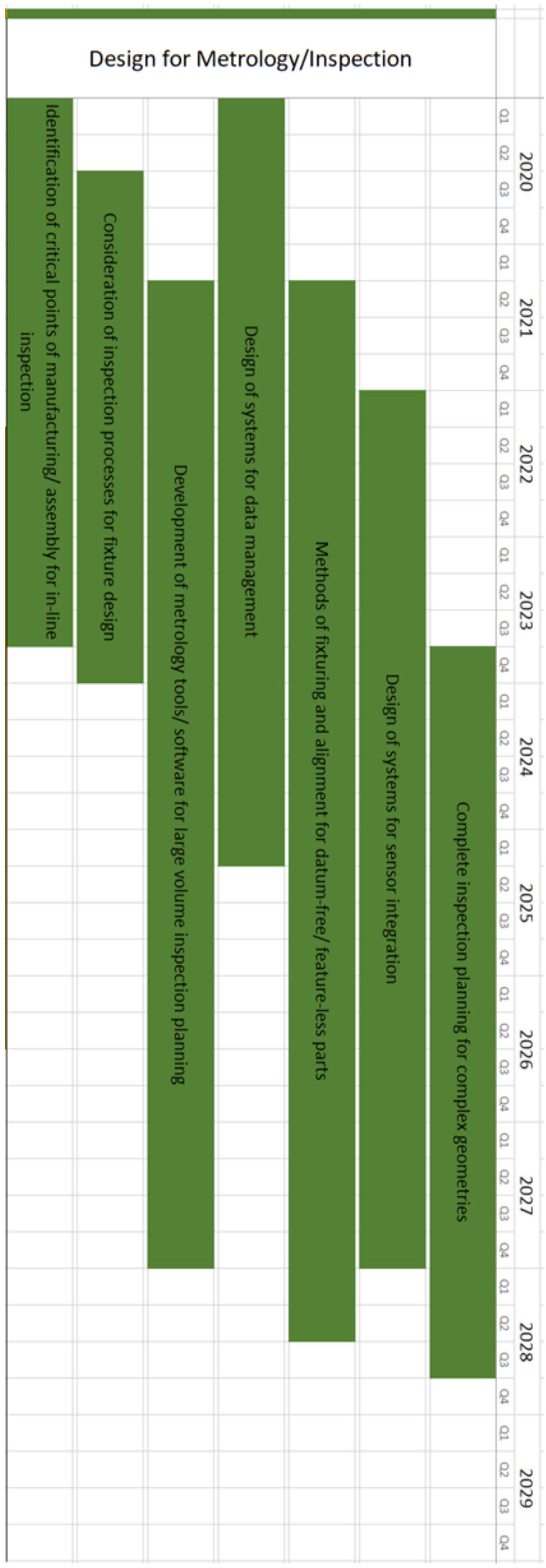
PROCESS INTEGRATION



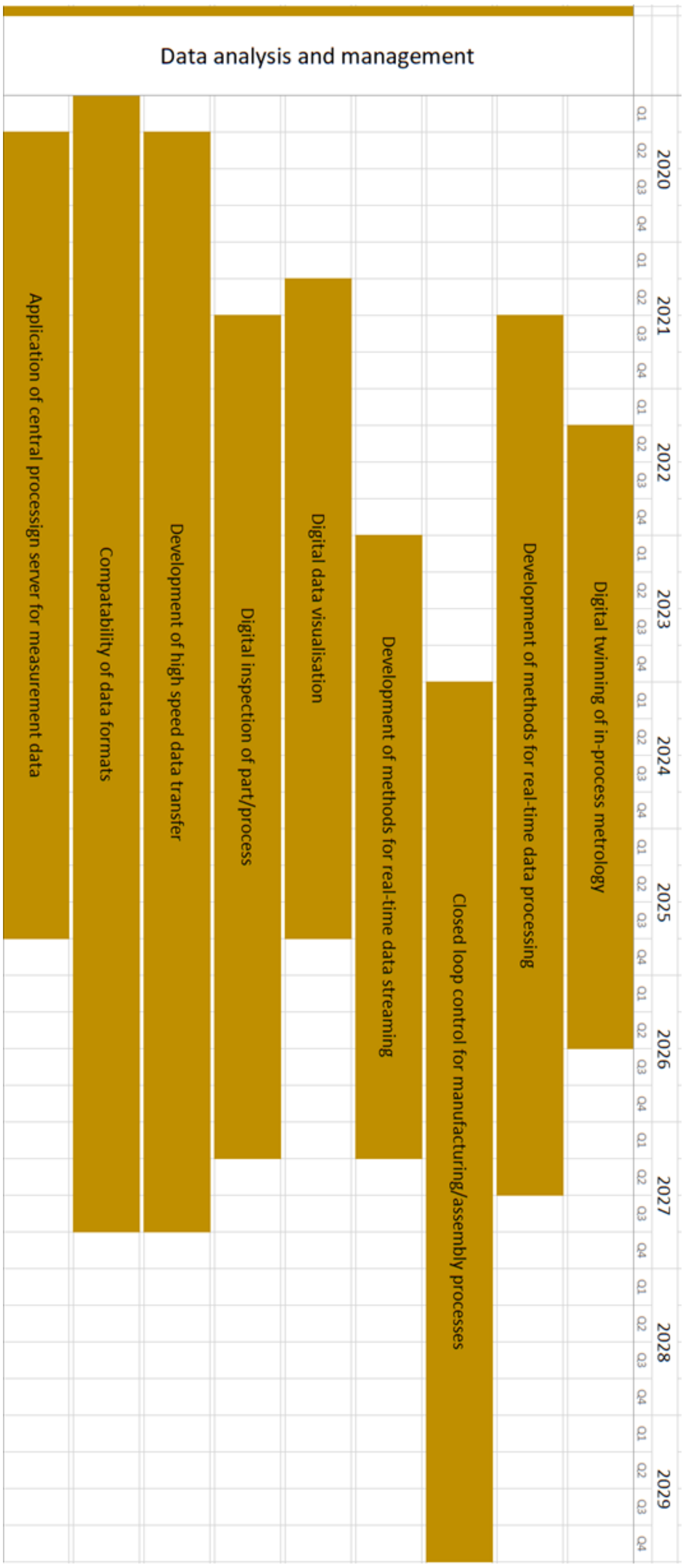
SENSOR DEVELOPMENT



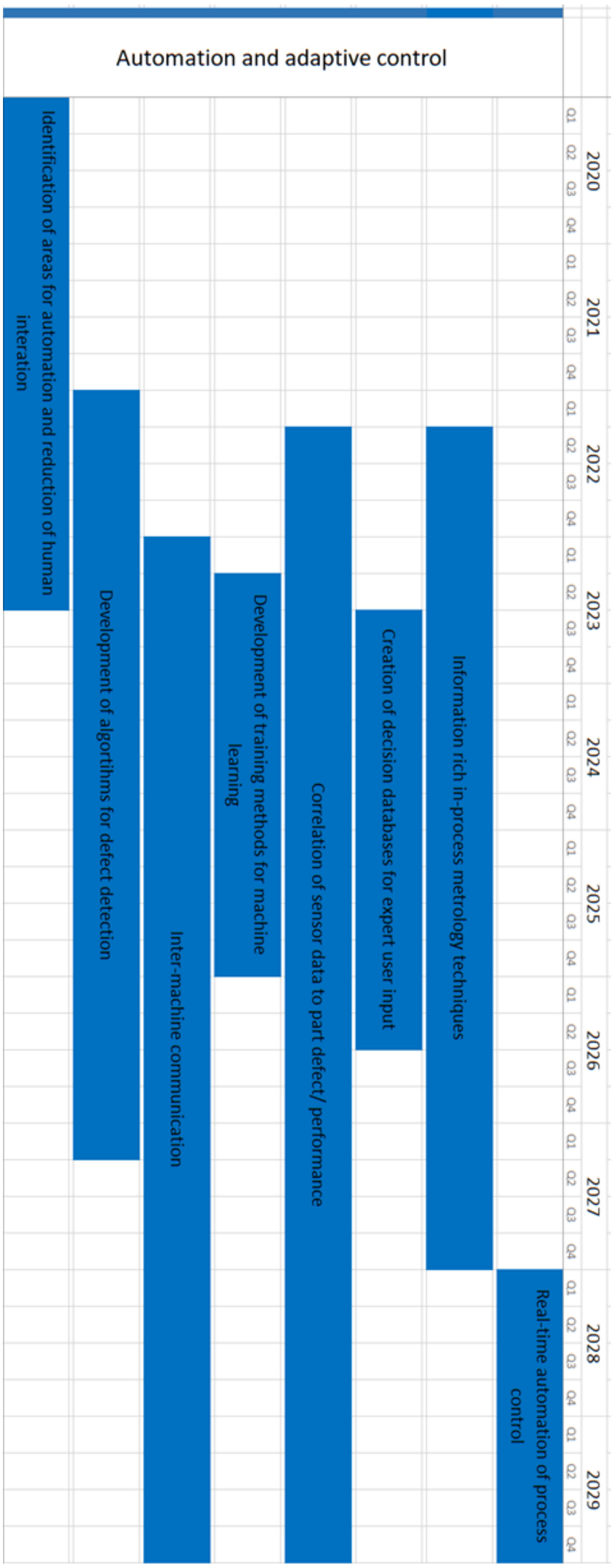
DESIGN FOR METROLOGY/INSPECTION



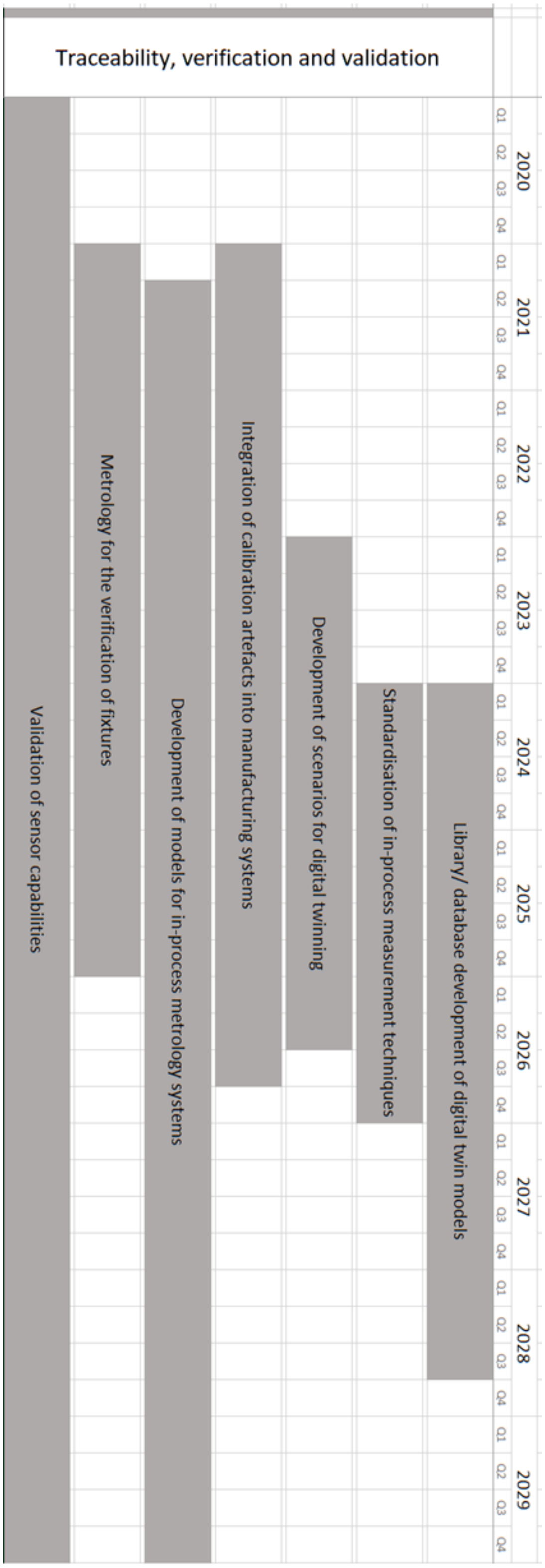
DATA ANALYSIS AND MANAGEMENT



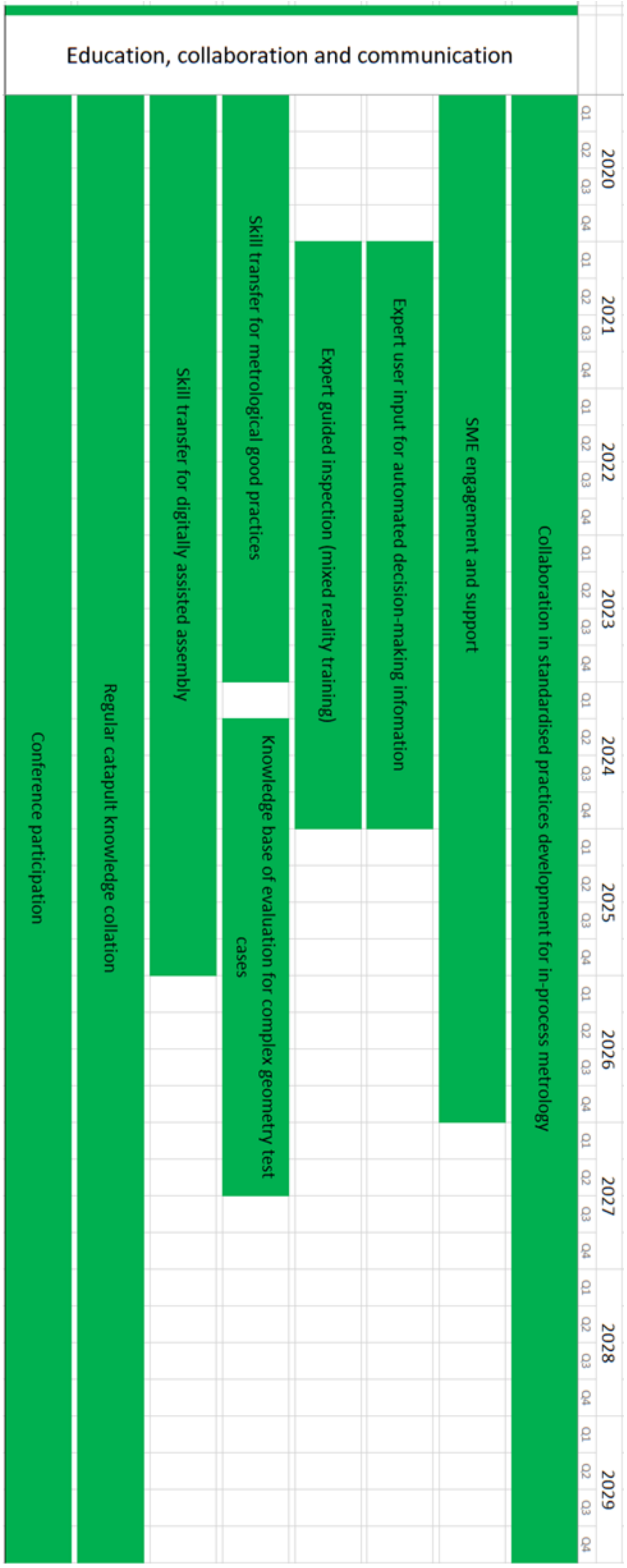
AUTOMATION AND ADAPTIVE CONTROL



TRACEABILITY, VERIFICATION AND VALIDATION



EDUCATION, COLLABORATION AND COMMUNICATION



REFERENCES

8GT: The 8 Great Technologies www.gov.uk/government/publications/eight-great-technologies-infographics

Carmignato S, De Chiffre L, Bosse H, Leach R K, Balsamo A, Estler W T 2020 Dimensional artefacts to achieve measurement traceability in advanced manufacturing *Ann. CIRP* in press

DeFisher S, Ross J 2019 Advancements in non-contact freeform metrology with datum structures *Optifab 2019* 11175 1117515

Doytchinov I, Shore P, Nicquevert B, Tonnellier X, Heather A, Modena M 2019 Thermal effects compensation and associated uncertainty for large magnet assembly precision alignment *Prec. Eng.* 59 134-149

du Plessis A, Yadroitsava I, Yadroitsev I 2019 Effects of defects on mechanical properties in metal additive manufacturing: A review focusing on X-ray tomography insights *Materials & Design* 108385

Du S, Xi L 2019 Online compensation manufacturing. In: *High Definition Metrology Based Surface Quality Control and Applications* (Springer, Singapore)

Everton S K, Hirsch M, Stravroulakis P, Leach R K, Clare A T 2016 Review of in-situ process monitoring and in-situ metrology for metal additive manufacturing *Materials & Design* 95 431-445

Gao W, Haitjema H, Fang F Z, Leach R K, Cheung C F, Savio E, Linares J M 2019 On-machine and in-process surface metrology for precision manufacturing *Ann. CIRP* 68 843-866

Grasso M, Colosimo B M 2017 Process defects and in situ monitoring methods in metal powder bed fusion: a review *Meas. Sci. Technol.* 28 044005

Hill J L, Prickett P W, Grosvenor R I, Hankins G 2019 The practical exploitation of tacit machine tool intelligence *Int. J. Adv. Manuf. Technol.* 104 1693-1707

ISCF: Industrial Strategy Challenge Fund www.gov.uk/government/collections/industrial-strategy-challenge-fund-joint-research-and-innovation

ISGC: Industrial Strategy: the Grand Challenges
www.gov.uk/government/publications/industrial-strategy-the-grand-challenges

Jiang X, Gao F, Martin H, Williamson J, Li D 2018 On-machine metrology for hybrid machining. In: Luo X *Hybrid Machining: Theory, Methods, and Case Studies* (Academic Press)

Jimenez-Cortadi A, Irigoien I, Boto F, Sierra B, Rodriguez G 2020 Predictive maintenance on the machining process and machine tool *Appl. Sci.* 10 224

Karner M, Glawar R, Sihn W, Matyas K 2019 An industry-oriented approach for machine condition-based production scheduling *Proc. CIRP* 81 938-943

Larsen L, Kim J, Kupke M, Schuster A 2017 Automatic path planning of industrial robots comparing sampling-based and computational intelligence methods *Proc. Manuf.* 11 241-248

Leach R K, Bourell D, Carmignato S, Donmez A, Senin N, Dewulf W 2019 Geometrical metrology for metal additive manufacturing *Ann. CIRP* 68 677-700

LeCun Y, Bengio Y, Hinton G 2015 Deep learning *Nature* 521 436-444

Lei P, Zheng L 2017 An automated in-situ alignment approach for finish machining assembly interfaces of large-scale components *Robotics and Computer-Integrated Manufacturing* 46 130-143

Li D, Wang B, Tong Z, Blunt L and Jiang X 2019 On-machine surface measurement and applications for ultra-precision machining: a state-of-the-art review *Int. J. Adv. Manuf. Technol.* 104 831–847

Lu W, Pagani L, Zhou L, Liu X, Wang J, Leach R K, Jiang X J 2019 Uncertainty-guided intelligent sampling strategy for high-efficiency surface measurement via free-knot B-spline regression modelling *Prec. Eng.* 56 38-52

Maier J 2017 *Made Smarter Review* (Department for Business EIS, The Stationery Office. London)

Maurya D K, Kumar A, Kaunoujiya S, Prasad D, Nath V 2019 Study and design of smart industry: a review. In: Nath V, Mandal J K *Nanoelectronics, Circuits and Communication Systems* (Springer, Singapore)

Monti F, Boscaini D, Masci J, Rodola E, Svoboda J, Bronstein M M 2017. Geometric deep learning on graphs and manifolds using mixture model CNNs *Proc. IEEE Conference on Computer Vision and Pattern Recognition* 5115-5124

Mutilba U, Gomez-Acedo E, Kortaberria G, Olarra A, Yagüe-Fabra J A 2017 Traceability of on-machine tool measurement: a review *Sensors* 17 1605

Mutilba U, Sandá A, Vega I, Gomez-Acedo E, Bengoetxea I, Fabra J A Y 2019 Traceability of on-machine tool measurement: Uncertainty budget assessment on shop floor conditions *Measurement* 135 180-188

NMS: National Measurement System: annual highlights 2018 www.gov.uk/government/publications/national-measurement-system-annual-highlights-2018

Papananias M, McLeay T E, Mahfouf M, Kadirkamanathan V 2019 A Bayesian framework to estimate part quality and associated uncertainties in multistage manufacturing *Computers in Industry* 105 35-47

Psarommatis F, May G, Dreyfus P A, Kiritsis D 2020 Zero defect manufacturing: state-of-the-art review, shortcomings and future directions in research *Int. J. Prod. Res.* 58 1-17

Qin Y, Qi Q, Scott P J, Jiang X 2019 Status, comparison, and future of the representations of additive manufacturing data *Computer-Aided Design* 111 44-64

Razvi S S, Feng S, Narayanan A, Lee Y T T, Witherell P 2019 A review of machine learning applications in additive manufacturing *ASME International Design Engineering Technical Conferences and Computers and Information in Engineering Conference* (American Society of Mechanical Engineers Digital Collection)

Senin N, Leach R K 2018 Information-rich surface metrology *Proc. CIRP* 75 19-26

Smith G T 2016 *Machine Tool Metrology: An Industrial Handbook* (Springer)

Stavroulakis P, Leach R K 2016 Review of post-process optical form metrology for industrial-grade metal additive manufactured components *Rev. Sci. Instrum.* 87 041101

Syam W P, Rybalcenko K, Gaio A, Crabtree J, Leach R K 2019 Methodology for the development of in-line surface measuring instruments with a case study for additive surface finishing *Opt. Lasers Eng.* 121 271-288

Tolle I, Lee J, Salvador D, Saville B, Yong P B, Marcuccilli G 2019 Defect learning with predictive sampling for process improvement *Proc. SPIE* 10959 1095930

Xiao J, Anwer N, Durupt A, Le Duigou J, Eynard B 2018 Information exchange standards for design, tolerancing and additive manufacturing: a research review *Int. J. Interactive Design Manuf.* 12 495-504

APPENDIX A – CONFERENCE AGENDAS

INTEGRATED METROLOGY FOR PRECISION MANUFACTURING CONFERENCE

Day 1

08:15-08:45	Registration
09:00-09:15	Welcome Talk – Richard Leach, Conference Chair
09:15-09:45	Keynote 1: Rob Dwyer-Joyce – University of Sheffield "Ultrasonic sensors for in-situ manufacturing process control"
09:45-10:15	Coffee & Networking
10:15-10:45	Session 1 Sensor development – State-of-the-art review - Claudiu Giusca, Cranfield University
	10:45-12:45 Session 1 Sensor development
10:45-11:05	Wahyudin P. Syam – University of Nottingham "A fast wireless focus variation probe for in-process surface measurement"
11:05-11:25	Tom Charrett – Cranfield University "3D positioning for industrial robotics"
11:25-11:45	Jeremy Coupland – Loughborough University "Synthetic aperture interferometry: High-resolution optical measurement over an exceptionally large field of view"

11:45- 12:05	Roger Artigas – Sensofar "Active illumination focus variation: rivaling confocal microscopy"
12:05- 12:25	Ivan Zorin – RECENDT "Optical coherence tomography for non-destructive testing and imaging applications"
12.25- 12.45	Ian McLean – Renishaw "Vision inspection advantages of mounting optical probes on five axis measurement systems"
12:45- 14:00	Lunch
14:00- 14:30	Session 2 Data handling – State-of-the-art review - David Butler, National Physical Laboratory
	14:30-16:00 Session 2 Data handling
14:30- 14:50	Rufino Bolado-Gomez – CW Fletcher "Thinking data in aerospace manufacturing – present & future at CW Fletcher"
14:50- 15:10	Moschos Papananias – University of Sheffield "Data informatics for multistage manufacturing"
15:10- 15:30	Clifford Brown – National Physical Laboratory "Communication and validation for smart metrology data in IoT networks"
15:30- 16:00	Coffee & networking
16:00- 17:30	Laboratory tours

18:30-21:00	Evening Meal

Day 2

09:00-09:30	Keynote 2: Mostafizur Rahman – Manufacturing Technology Centre "Integrated information for improved quality"
09:30-10:00	Coffee & networking
10:00-10:30	Session 3 Process monitoring – State-of-the-art review - Jon Stammers, Advanced Manufacturing Research Centre
	10:30-11:50 Session 3 Process monitoring
10:30-10:50	Gorka Kortaberria – IK4-Tekniker "Integrated volumetric error mapping solution for traceable on-machine tool measurement"
10:50-11:10	Tim Rooker – IDC Machining Science "Machining centre performance monitoring with calibrated artefact probing"
11:10-11:30	Liam Blunt – University of Huddersfield "In process surface metrology for roll to roll manufacture of printed electronic devices"
11:30-11:50	Florian Schwimmer – Alicona "In-line measurements with focus variation as enabler for an autonomous manufacturing cell"
11:50-13:00	Lunch

13:00-13:30	Keynote 3: Rab Scott – Advanced Manufacturing Research Centre "Factory 2050: Manufacturing with data"
13:30-14:00	Session 4 Process control – State-of-the-art review - Andrew Longstaff, University of Huddersfield
	14:00-15:40 Session 4 Process control
14:00-14:20	Chris Jones – National Physical Laboratory "Advances in metre traceability for industrial process control"
14:20-14:40	Oliver Martin – Insphere "Benchmarking performance for a new rapid machine tool verification process"
14:40-15:00	Dariusz Ceglarek – University of Warwick "Closed-loop in-process quality improvement: 'Right-first-time' production through digital technologies"
15:00-15:20	Patrick Keogh – University of Bath "Robotic machining with embedded feedback"
15:20-15:40	James Kratz – National Composite Centre "Flow-front measurement and simulation in liquid composite moulding"
15:40-16:40	Open forum and discussions
16:40-17:00	Closing remarks

INTEGRATED METROLOGY FOR ADDITIVE MANUFACTURING CONFERENCE

08:15-08:45	Registration
09:00-09:15	Welcome Talk – Richard Leach, Conference Chair
09:15-09:45	Keynoe 1: Bianca Maria Colosimo, Marco Grasso – Politecnico Milano "In-situ monitoring in AM: state of the art and future perspectives"
09:45-10:05	Richard Leach – University of Nottingham "Metal AM surface topography"
10:05-10:30	Coffee & networking
	10:30-12:10 Session 1
10:30-10:50	Thomas Kissinger – Cranfield University "In-process layer height measurement in Wire+Arc AM using range-resolved interferometry"
10:50-11:10	Liam Blunt – University of Huddersfield "The Development of and In-process metrology system for Electron Beam Additive Manufacturing"
11:10-11:30	Nick Jones – Renishaw "In process monitoring for laser powder bed fusion – current capabilities and future perspectives"
11:30-11:50	Abdul Syed – Coventry University "Structural integrity of additive manufactured titanium alloy: impact of defect size, shape and location"

11:50- 12:10	Andrew Dickins – University of Nottingham "Design of an In-situ Metrology System for Additive Manufacturing"
12:10- 13:00	Lunch
	13:00-14:40 Session 2
13:00- 13:20	Hay Wong, Peter Green – University of Liverpool "In-Process Electron Beam Melting Metrology with Electronic Imaging"
13:20- 13:40	Ben Dutton – Manufacturing Technology Centre "Challenges & Opportunities for In-process Inspection"
13:30- 14:00	Fangda Xu – University of Bath "Process Monitoring for Wire-Arc Additive Manufacturing"
14:00- 14:20	Iain Todd – University of Sheffield "Machine learning for control of process outcomes in AM"
14:20- 14:40	Abdul Haque – Advanced Manufacturing Research Centre "The importance of process monitoring during Selective Laser Melting"
14:40- 15:00	Summary and open session
15:00- 15:30	Coffee & networking
15:30- 16:30	Laboratory tour

ABOUT THE HIGH VALUE MANUFACTURING CATAPULT

The High Value Manufacturing Catapult creates the conditions for economic growth by enabling UK manufacturers to achieve significant improvements in their performance and productivity. We do this by providing open access to world-class innovation capability and technical expertise, enabling companies to embrace different ways of working, adopt new technologies and achieve step-change in their performance.

To find out more about the High Value Manufacturing Catapult, please visit: hvm.catapult.org.uk

High Value Manufacturing Catapult
Regus Building
Blythe Valley Business Park
Solihull
B90 8AG

ABOUT THE AUTHOR

Richard Leach is Professor in Metrology at the University of Nottingham and heads up the Manufacturing Metrology Team. His research themes include the development of methods for measuring 3D structures, development of methods for in-process surface manufacture and measurement traceability. He is a leader of several professional societies, works closely with the High Value Manufacturing Catapult and is a visiting professor at Loughborough University and the Harbin Institute of Technology.

If you have any questions about this report, please contact the author via email: Richard.Leach@nottingham.ac.uk

Supported by:

Engineering and Physical Sciences Research Council

University of Nottingham UK | CHINA | MALAYSIA