Information-rich metrology: Changing the game

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1. Manufacturing metrology

To support the manufacture of next-generation high-value products, increased reliance will be placed on metrology. This article will discuss an approach to metrology that, in our opinion, has the potential to significantly enhance the metrology capability in advanced manufacturing. First, let us briefly review the need for metrology in manufacturing. Lord Kelvin said: "If you cannot measure it, you cannot improve it", and this simple statement captures a great deal about why measurement is an essential part of manufacturing. The following are some of the primary reasons why we put so much effort into measuring what we manufacture:

- To know whether a part is fit-for-purpose; for example, will a shaft fit within a hole, but still give enough clearance to allow the flow of lubricating fluids?
- To allow assembly of complex components; without understanding the dimensions of parts and their associated tolerances, it becomes almost impossible to fit one part to another – this is an especially relevant point when assembling parts that have been manufactured in different companies or different parts of a company.
- To allow control of a manufacturing process; there is little control without measurement, for example, we may want to change the speed of a cutting tool depending on the surface texture that it is producing – we, therefore, need to measure the texture (or something from which we can infer texture) during the machining process.
- To avoid unnecessary scrap material and redundant processing time; metrology is essential for quality control which allows us to attempt things such as net-shape manufacturing – getting it right first time.
- To improve energy-efficiency; the less repeat manufacturing processes that are required, the lower the energy required to produce a product.
- To give customers confidence in a product; "customers" in this context could be another manufacturing concern that needs to use your components – without tolerances and quality control, there will be a lack of confidence in the assembly processes down the line.
- To comply with quality standards, such as ISO 9001, and with established quality control techniques, including six sigma and process capability indices.

For the above, and many more reasons, metrology is essential for manufacturing. While traditionally metrology has been applied to the inspection of the final part, after the manufacturing process is completed, nowadays the trend is to bring metrology in to the production line. This may just mean performing part inspection right after each step of the manufacturing process (for example, between a roughing and a finishing operation in a machine tool), or we can push integration even further by carrying out the measurement tasks during the execution of each individual manufacturing operation, where the nature of the operation allows it (for example, within an additive manufacturing process, measuring the properties of a layer while it is being fabricated). Also, when considering, integration between metrology and manufacturing, consideration about the measurement data are important. One integration scenario may see a measurement triggering an alarm if something goes wrong during a manufacturing operation (i.e. detection of an out-of-control condition); more complex integration scenarios may see some form of implementation of feedback mechanisms, for example, the triggering of a corrective action, or the real-time modification of some manufacturing process control parameter to bring the process back to an in-control state.

Such integrated metrology needs to the compatible with the manufacturing cycle time (we do not want metrology to slow down the process, or at least not prohibitively), and measurement systems need to be spatially located to be compatible with the type of integration: i.e. on the production machine, or close enough if measurement is to be performed between manufacturing stations.

The above scenarios can be summarised by a series of commonly adopted terms, which we define here under the umbrella term "Integrated metrology" (see Figure 1):

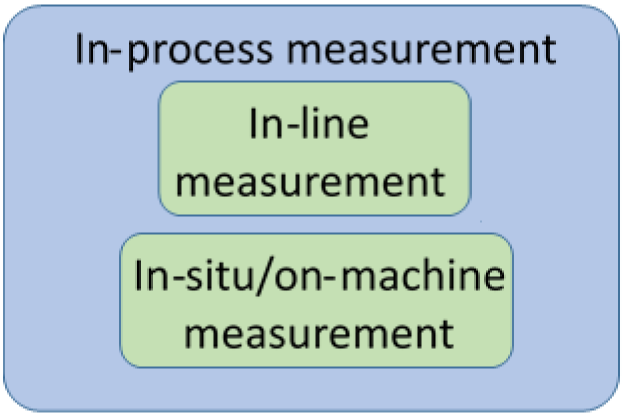

Figure 1 Integrated metrology

- *In-process measurement*: An instrument or sensor module that measures an aspect of the product quality or the property of a machine during or after a manufacturing processes, regardless of the location of the instrument or sensor module. The instrument or sensor module's placement depends on the characteristics of the machining process, for example, how it is mounted or whether it is separated from the machining operation.
- *In-situ/on-machine measurement*: An instrument or sensor module that is directly mounted into the manufacturing process. The module continuously or momentarily measures one or several parameters of a product or the property of the machine during the machining process to control the process and/or the quality of the product.
- *In-line measurement*: An instrument or sensor module that is mounted separately from the machining process and automatically inspects the quality of a product shortly after the machining process is complete.

Developments in integrated measurement and control have allowed significant enhancement of advanced manufacturing techniques and marked improvements in surface texture and material properties, along with a reduction in process variation and defects. Integrated measurement and control technologies can also offer cost reductions and process efficiency improvements, but the scale of up-front investment required can often seem daunting, and the benefits may not be easily quantified. Cost considerations aside, there are a number of potential barriers to integrated metrology that can prevent its wide-scale adoption in industry. These include, but are not limited to the following. Note that we will concentrate mainly on dimensional and surface metrology using optical technology in this article, but many of the arguments can be generalised to any metrology discipline.

i. *Measure over larger dynamic ranges*: all measuring instruments have a finite dynamic range, defined here as the ratio of their range to their resolution in terms of either lateral and/or height capabilities. Often the trade-off is to have either a large range or a high resolution, but rarely both. For example, in optical surface metrology, there are two distinct classes of instrument which are commercially available: 1. those that measure over large areas (metres squared) with low spatial resolution – a few hundreds of micrometres (for example, fringe projection, photogrammetry and moiré interferometry) and 2. those that measure over small areas (up to a few millimetres squared) with spatial resolutions of the order of a micrometre (for example, coherence scanning interferometry, confocal microscopy and focus variation microscopy). Essentially, the former class is camera-limited (sensor resolution and depth of field issues), while the latter is objective-limited (diffraction limited through finite numerical aperture, see section 0) and can be prohibitively slow due to the need for scanning in both lateral and often axial directions. In order to meet the demands of advanced manufacturing, there have been several attempts to try and combine the two classes, but more progress is required before such hybrids can be used in earnest. This dynamic range issue is especially problematic for industries that manufacture small features over large areas in a highly parallel fashion, for example, for roll-to-roll applications such as printed electronics.

ii. *Measure higher slope angles*: all optical instruments are fundamentally limited by finite slope measurement capabilities, mainly due to their numerical apertures and, in many cases this limitation is related to the dynamic range limitation above. This fundamental limitation will be treated in some depth in section 0, as it is one of the key limitations that hinder progress in optical metrology.

iii. *Measure difficult materials:* all surface measuring instruments have limits on the types of surface that they can measure. Also, where mathematical models of the imaging or scattering process are necessary, some instruments make assumptions about the surface being measured that may not be met in practice, for example, that the surface is a highly-reflecting metallic surface. Polymer and ceramic surfaces can cause significant issues due to translucency and rough surfaces can cause multiple-reflection and slope effects (see *ii*). Surfaces with mixed materials and/or produced using multiple processes are especially challenging, and surfaces produced by additive manufacturing have significant material challenges for optical instruments.

iv. *Measure at high speed:* for integrated metrology, and especially for in-line/in-situ metrology, there must be significant increases in the speed of measurement. The high-speed metrology task is increasingly limited by the fundamentals of optical interrogation of the surface, such as: the compromise between spatial resolution and field of view; the loss of effective spatial resolution due to motion blur; or the dynamic range of optical properties across the inspected region. Such limits imply that faster “brute-force” measurement of the whole surface cannot be a solution. Whilst there have been valiant attempts to speed up conventional measurement techniques, often speed increases of several orders of magnitude are required for integrated metrology to become realistic. In order to overcome the metrology speed challenges, it is essential to exploit a priori knowledge about the production task, the nature and functional significance of relevant defects, and any potential repair steps to dramatically simplify the measurement task. Development of existing measurement techniques to simplify integration, hybridisation and increased environmental tolerance will also help. A range of research strands needs to be followed including: optical system modelling and defect extraction, global control of substrate and defect location, intelligent sampling and data throughput, and fast feature inspection.

The conventional approach to address the issues above is simply to improve our existing measurement technologies. But, as has been pointed out in *iv* above, there are a number of reasons why this is not the whole solution. In many cases, we have come up against barriers that prevent us from significant further improvements in instrument performance. Such barriers are due to limitations in current technology and due to the fundamental laws of physics (or a combination). Examples of limitations due to physics include: the shot noise limit, either due to the discrete nature of electrical charge in electronics or to the particle nature of light in optical detectors; the diffraction limit in optics, due to the wave nature of radiation, there is diffraction caused by the limiting edges of the optical system's aperture (this means a point will always be imaged with finite blur); the slope angle limitation in an imaging system due to its finite numerical aperture (see below); and the limit on sampling due to Shannon's theorem. Examples of technology limitations are the finite processor speed or memory limits of computing systems. When we attempt to produce integrated measurement solutions, such technology limits are a frequent issue and often the only way around this is to use pre-processing methods, for example adaptive or intelligent data reduction and sampling techniques, effectively trying to reduce the data overhead.

2. Information-rich metrology

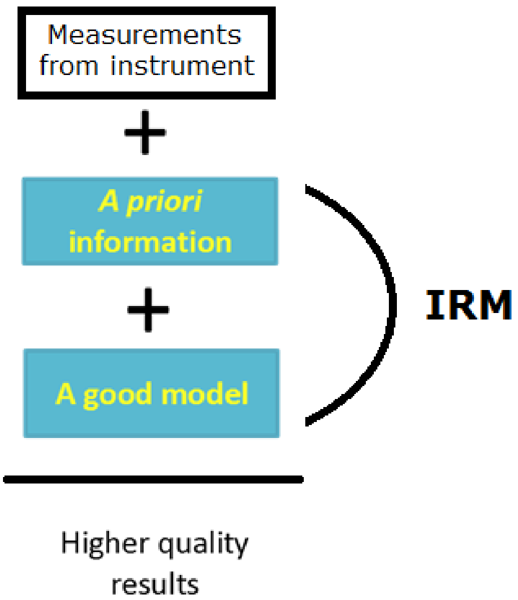

Figure 2 The "information-rich metrology" philosophy

Information-rich metrology (IRM) is a term that we introduce to refer to the use of any type of additionally-available information to improve a measurement process. Information may come from knowledge of the manufacturing process, knowledge of the object to the measured, and/or knowledge of the physical interactions/principles underlying the measurement technology itself. Additional information may be pre-existing (i.e. "a priori"), or obtained through other measurement processes, even concurrently to the measurement we are aiming to improve. The idea of using available information related to the product, or process, or product-measurement-instrument interaction, makes intuitive sense because metrology in manufacturing takes place in controlled and very predictable conditions, with a sensible amount of information which is known in advance. Often when we manufacture something, and especially when we use digital manufacturing methods, we have a large amount of information about the object being manufactured, for example, the CAD data gives us the nominal form and we have usually characterised the surface texture to a high degree of confidence. Analogously, we do have – or we can acquire – a significant amount of information about the manufacturing process, in terms of its capability, the features and defects it generates, the materials it is designed to operate with, and the types of geometries and surfaces it typically produces. Most of the above information becomes available at product development and at manufacturing process planning, and we are asserting that such information may also bring benefit to metrology.

One of the most promising paradigms for IRM is based on using additional information about the manufacturing process and the object that is fabricated, to develop improved mathematical models that describe the interactions between the measured object and the measurement probe (see Figure 2). In practice, mathematical models that describe physical principles and phenomena underlying many measurement technologies are already available, although one has to be careful that over-simplifications are no abused. In optical measurement, for example, many models have been developed over the decades, to support the theory of focus-variation measurement, coherence-scanning interferometry, confocal microscopy, fringe projection, photogrammetry, etc. It is safe to say that the totality of current commercial optical measurement systems are already making use of complex mathematical models to interpret raw data acquired through their probes. However, because such models aim to be general, which means that they must be applicable with little prior knowledge of the measurement scenarios, they can make very few assumptions about the nature of the surface which will be measured, the material properties they will encounter, etc. Thus, such models are limited in the information they can provide. A typical example is the interpretation of signals originated by light captured by the detector after multiple reflections and scattering. Trying to reconstruct what determined the patterns captured by the detector typically implies the solving of complex (often non-linear) inverse problems, which are typically unsolvable or ambiguous without resorting to additional sources of information. The advantage of working in the scenarios typically encountered in manufacturing metrology is that we often have such additional information, for example, because we have a rough idea of what the part may look like, and/or because we have a clear idea of what type of signature features a specific manufacturing process leaves on a surface. In other words, we have a lot of information, currently not used, which we may include to help develop better models, which in turn help us better interpret the raw data captured by the instrument.

The predictability of operating conditions, and the wealth of information available in a typical manufacturing metrology scenario explain why our research in IRM is focusing on one of its most promising paradigms, that is, to develop advanced models of probe-surface interaction in order to improve measurement quality, whilst using externally available information (from the product, process, or other) to develop such models.

Several examples will be given in the following, together with additional examples that show that a priori information has also additional uses, other than for improving measurement models, but before proceeding, it is important to discuss why IRM is important to manufacturing metrology, and to integrated metrology in particular.

As stated earlier, central to IRM is the aim to improve measurement quality. Quality is here intended as a generic term encompassing multiple facets. Improving quality may mean: reducing measurement times, improving measurement performance indicators (accuracy, precision, etc.), expanding the range of covered scales (spatial resolution and range - in terms of spatial frequencies we will often refer to expanding the bandwidth of a measurement), and improving coverage, intended as the capability to reach surfaces which may be harder to reach, for example measuring beyond the maximum permissible slope for a given measurement technology (see below). Improving measurement quality may also mean that we can obtain the same results that we obtained before, but at a fraction of the costs, or of the time, or with smaller, cheaper, more rugged and more affordable instruments; these are all essential aspects to better integrate metrology in to the production line.

IRM is nothing new; the use of a priori information to enhance a measurement system's operating bandwidth has been carried out for hundreds of years. Perhaps the first and most well-known example of IRM is that of optical super-resolution in microscopy and astronomy. This, along with a number of further examples of IRM are analysed in detail in the next section.

3. Examples of IRM

Super-resolution imaging

The resolution of an imaging system is a measure of the system's ability to faithfully output fine detail present in the input. All imaging systems are associated with limits of resolution that may relate to properties of the probe, detector or surrounding environment. It is often convenient to divide resolution into the lateral and axial limits, which lie perpendicular and parallel to the imaging system's optical axis, respectively. The development of optical interferometry has pushed the resolution limit in the axial direction to below 1 nm (it is essentially noise limited). However, advances in lateral resolution have proved more difficult to achieve. One technique that has seen significant improvement in lateral resolution is non-linear fluorescence microscopy, where molecular resonances are used to enhance the resolution. These non-linear techniques are generally not applicable to the measurement of manufactured surfaces, and so in this section only issues relating to the lateral resolution in linear, far-field imaging systems will be discussed.

The theory of geometrical optics predicts that light can be focused to an infinitely small point. By this logic, no fundamental limit to the resolution of an imaging system exists. However, in the more physically accurate theory of wave optics, the phenomenon of diffraction causes the focal spot to take on a characteristic shape which has a finite size, the dimensions of which are related to the imaging system's angular aperture and the wavelength of light. In certain circumstances, however, the limit imposed by diffraction can be surpassed, and this is where we focus our discussion to illustrate IRM.

The advent of digital image detectors expedited a paradigm shift in the understanding of resolution. Numerical fitting routines allowed point sources to be resolved at separations significantly below the classical (diffraction) resolution limit. Thus it became accepted that under *certain circumstances* the limit to resolution lies in the quality of the image (and thus how well it can be modelled) and this is determined by the signal-to-noise ratio. The certain circumstances alluded to here refers to the presence of a priori knowledge of the object. The existence of a priori knowledge of an object allows the imaging process to be optimised for resolving specific structures on the object surface. This knowledge also facilitates the use of image processing algorithms that use concepts such as bandwidth extrapolation, which allow estimation of object spatial frequencies that lie significantly above the classical limit. Imaging outside the diffraction limitation is often called "super-resolution", although there is much confusion about the exact definition of the term. Here, we define super-resolution, as the ability to image (and be careful here – we mean image, not just detect the presence of) features outside the spatial bandwidth dictated by the diffraction limitation of the imaging system. Clearly, this form of super-resolution is IRM, as it requires both a priori information and accurate models of the measurement scenario.

In the context of IRM, use of such super-resolution techniques may increase the bandwidth of the measuring instrument so as to allow for resolution beyond the classical diffraction limit. However, in practice the feasibility of bandwidth extrapolation is limited by the noise level in the measured data and the accuracy of the a priori knowledge of the object. Such techniques have been used in astronomy and microscopy for many years, and they have been employed with limited success in manufacturing metrology.

High slope measurement

Complex surfaces often have features which have high slope angles, either through design, for example prismatic arrays for safety signage, or due to the nature of the manufacturing method, for example in additive manufacturing. The most complex surfaces may have very large ranges in terms of spatial frequencies (and hence surface slope angles), for example, a highly aspheric surface with a micro-scale Fresnel grating. Deterministically-textured surfaces with complex geometries are abundant in mechanical engineering fields for such applications from fluid control, adhesion, tribology and bio-compatibility, and such surfaces present significant metrology challenges. Instruments that use contrast to detect the surface (for example, focus variation microscopy), require a certain degree of roughness on the surface (or other contrast mechanism), therefore, can detect out-of-aperture slope angles. However, such instruments cannot measure smooth surfaces and the reconstruction process is complex and prone to error. With fringe projection systems, powder sprays are used to give the surface a matt coating to exploit the use of scattered light and hence capture information from slopes outside the aperture range, but can contribute several micrometres to the measurement uncertainty.

The above methods to overcome the fundamental slope limitation either require the surface to have a specific nature (for example, to be rough on specific scales) or require a coating to be applied. However, another potential approach to extend the slope angle limitations of optical instruments is to use rigorous modelling of the optical interaction with the surface to solve the non-linear inverse problem of multiple reflection. For example, in coherence scanning interferometry (CSI), the effects of multiple scatter would be considered a source of error and, therefore, neglected. However, multiple scattering can be considered as a mechanism that redirects into the instrument light that would otherwise fall outside the limits of the numerical aperture. Consequently, the effects of multiple scattering have the potential to reveal 3D features described by spatial frequencies that are outside of the usual bandwidth of the instrument (i.e., that would be described by simple linear imaging theory). For general 3D objects, a priori information is needed to distinguish the effects of single and multiple scattering. For the case of surfaces, however, knowledge that the scattering is due to the interface of two homogenous media can be sufficient. This method has been demonstrated as an iterative optimisation routine using finite element analysis to calculate the optical fields scattered from a silicon step and is illustrated in Figure 3. Figure 3 (left) shows computed CSI fringes that clearly reveal the upper and lower horizontal surfaces of the step. From this data (the a priori), a more accurate scattering model can be implied, as shown in Figure 3 (centre). The changes to this model necessary to explain the data in Figure 3 (left) were then computed resulting in the higher order interferogram shown in Figure 3 (right). The vertical wall of the step is now apparent and further iterations of the method can be applied. Such a method for measuring outside the numerical aperture limit can be used to measure a range of structures, for example, high aspect ratio holes and pillars found in MEMS devices or X-ray optics.

Figure 3 Left: measured CSI interferogram. Centre: finite element model from CSI interferogram. Right: second-order CSI interferogram, clearly showing the vertical sidewall (results from work at Loughborough University)

The results shown in Figure 3 are a good illustrative example of IRM as they have all the essential ingredients shown in Figure 2 in an obvious manner. However, the research effort required to realise such a technique should not be underestimated. There are significant challenges in performing the measurements (mainly in optimising the contrast of the second-order and potentially higher-order fringes), for the modelling of the second-order effects (a finite element model was used in this example) and in the interpretation of the (information-rich) data. There may be opportunities to use this approach with other optical systems and for rough surfaces (perhaps using low aperture measurements as the a priori data), but the rigorous models need to be developed and optimised to operate in reasonable times.

Sensor fusion

Information to improve the measurement result may not necessarily be available ahead of time (a priori), but may be acquired in parallel through other means from the same object. Information may also simply consist of other measurements in addition to the one that must be enriched. By using multiple measuring instruments, configurations, setups and sensors, possibly but not necessarily covering different ranges, resolutions, viewpoints, slopes, etc., it is possible to use each measurement result as information to improve the other measurements. Therefore, in a sense, any measurement result on the same object may play the role of a form of a priori for any other. Multiple measurements on the same part may in some cases be performed in parallel. In such cases, the concept of a priori is blurred into the concept of concurrency, but the general idea of IRM does not change: an "external" source of information enters the dual system formed by the instrument and the measured object, and helps improve the results. The approach of using multiple measurements from multiple instruments/sensors is often referred to as "multi-sensor data fusion". Fusion refers to the strategies which we adopt to combine the information, or more in general, to use the information to improve the final result (in terms of quality, quantity and/or coverage). There are multiple general approaches to the problem of multi-sensor data fusion.

In sequential fusion, the information acquired with an instrument is used to support measurement planning for the next. So we can measure a large surface with a fast and low-resolution method, just enough to recognise the presence of more critical regions on which to concentrate, which are then addressed with higher resolution, slower systems. Such an approach would classify as IRM, as the information obtained from the first dataset would be used as a priori data, to guide the setup for the second measurement.

In complementary fusion, measurements are run in parallel or in sequence, but are designed to capture complementary aspects of the object or surface. For example, two imaging devices are pointed at different angles to capture different slopes, or work at different wavelengths to capture different spatial frequencies, or simply point at different, typically adjacent regions of the same surface. The idea is that the combined result can achieve a larger coverage, for example, in terms of maximum measurable slopes, or spatial extent of the measured area, or ratio between range and resolution, or range of wavelengths. Again, these are examples of IRM, except that the concept of a priori is blurred, because typically all sources of information contribute in parallel to the final result.

In concurrent fusion, multiple measurements are designed to cover – at least partially - the same targets, but typically at different trade-off points between measurement cost/time/density and quality (accuracy/precision). The idea is that the higher-quality measurement could be used to improve the lower-quality one. For example, a fast, high-density point-based measurement system or low precision and accuracy may be used to cover a large region very quickly and cheaply (maybe a low-cost fringe projection system). Then a slow, low-density, very accurate system (maybe a touch probe) may be used to acquire only a few points in key areas, and these points may be used to correct the high-density dataset, improving its overall quality. The concurrent fusion approach typically implies the development of statistical models that explain how to use the high-quality dataset to modify the low-quality one. Several statistical methods have been developed and are being developed for this purpose.

The case previously discussed, of using a measurement result to input information in the development of an instrument-surface interaction model for another instrument, can be seen as another example of sequential data fusion.

At Nottingham we have a wide range of measurement solutions, covering a large range of scales, resolutions, measurement technologies, speeds, etc. and we are developing a suite of ways in which these methods can be combined.
Figure 4 shows a schematic representation of a system we are developing for in-process measurement in metal additive manufacturing. Form data from fringe projection (the projector and cameras in the figure), texture data from deflectometry (the distributed light array and cameras in the figure) and a thermal camera is fused together to create a holistic measurement that is more than the sum of the individual measurements (for example, the rapidly changing emissivity can be monitored and used to calibrate the thermal camera response).

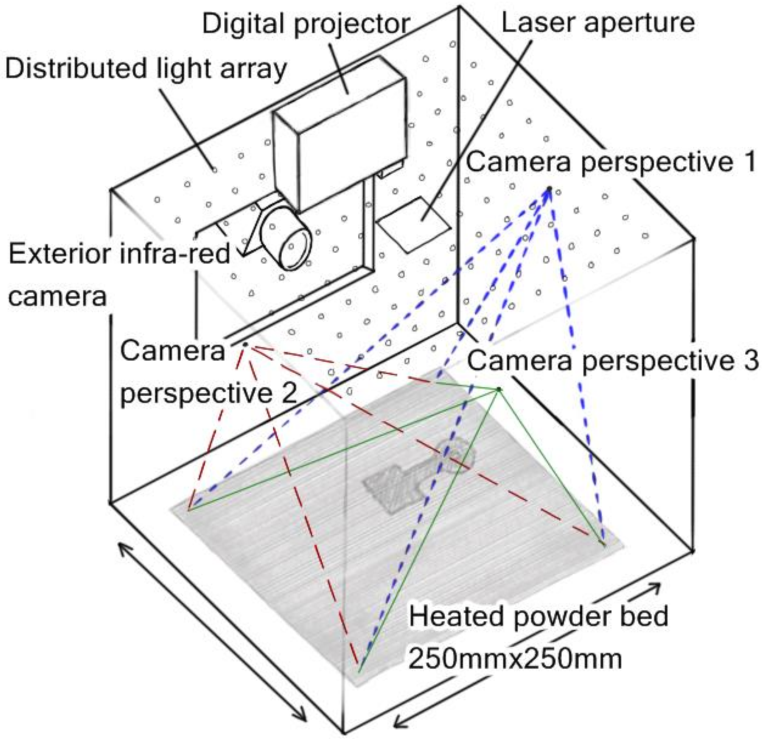

Figure 4 Example of data fusion in additive manufacturing using a combination of fringe projection, deflectometry and thermal imaging

Measurement enhancement using artificial intelligence

Artificial intelligence (AI) promises to be one of the most disruptive technologies of the next century, but researchers are up against critics who claim that it is nothing but another hype cycle of the same old recycled technology. The main reason for the new 'hype' in the commercial market today is mainly the availability of ubiquitous multi-core GPU computing, which enables the low-cost training of simple AI networks at home or in small businesses. Another reason is the proliferation of low-cost and relatively powerful computing platforms (such as the Raspberry Pi which retails for well under £100) which can take advantage of trained models to perform autonomous tasks. With the advent of the Internet of Things, AI algorithms on low-cost platforms will become even more pervasive and ubiquitous in society in the near future, and manufacturing industry is trying to position itself in order to be at the forefront of AI technology.

In terms of IRM, AI can be used to take advantage of the a priori data, the measured object (even past measurements) and, in combination with a functional measurement model, accelerate the measurement procedure and make it more efficient. An example of IRM which leverages AI to perform the measurements can be found in the microelectronics industry, where scatterometry data is used to accurately predict track resistance and, therefore, pre-empt failures in integrated circuits. The advantage in doing this is that silicon wafers can be discarded early in the manufacturing cycle to avoid expensive processing and testing further down the manufacturing line, thus avoiding the time required to produce and test the wafer at the end of the process.

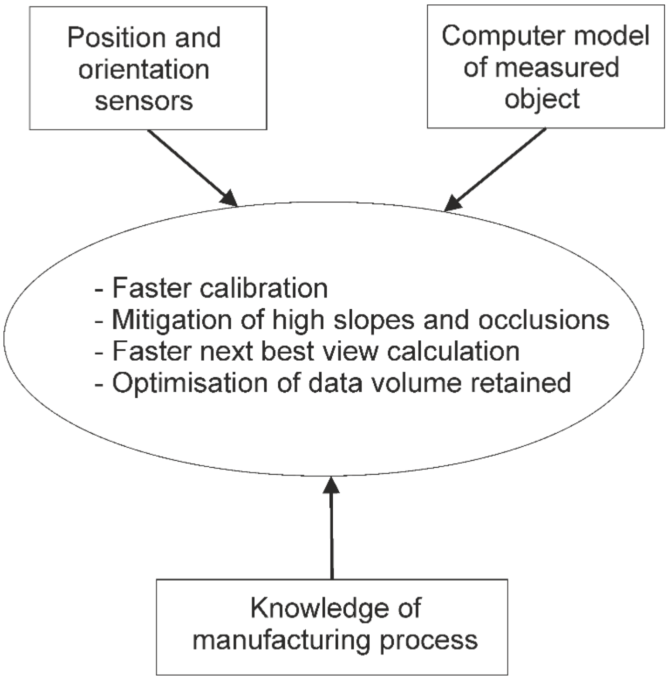

Figure 5 A priori data used for the fringe projection system under development at Nottingham

AI can also assist within an actual measurement system by converting the various parts of the measurement system (for example, cameras, stages, light sources) into smart 'agents' and thus viewing the machine as a 'perceptive agency', with agents working collaboratively to optimise the measurement result in terms of accuracy and coverage on a specific object. At Nottingham, we are currently developing a system to measure the 3D form of complex components (our main target industry is additive manufacturing). A fringe projection system is effectively converted into a 'perceptive agency' that is able to predict the source and camera positions (using inverse rendering) with respect to the measured object in real time, i.e. a frameless, self-calibrating measurement system. In fringe projection, where either the camera or projector setup can change significantly between measurements or the object needs to be tracked, self-calibration has to be carried out frequently to keep the measurements accurate. It is common to use methods developed initially for photogrammetry for the calibration of the camera(s) in the system in terms of extrinsic and intrinsic parameters. To calibrate the projector(s), an extra correspondence between a pre-calibrated camera and an image created by the projector is performed. These recalibration steps are usually time consuming and involve the measurement of calibrated patterns on planes, before the actual object can continue to be measured after a motion of a camera or projector has been introduced in the setup and hence do not facilitate fast and efficient 3D measurement of objects. By employing and combining a priori information via inverse rendering, on-board sensors, deep learning and leveraging a graphics processor unit, we have developed a fine camera pose estimation method which is based on optimising the rendering of a model of a scene and the object to match the view from the camera (see Figure 5). We have found that the success of this calibration pipeline can be greatly improved by using adequate a priori information from the aforementioned sources. The ultimate plan is to have a simple-to-use projector and camera set-up that can be reconfigured for different 3D object shapes and can allow for effects such as shadowing, occlusions and different textures. The complexity of the system is transferred to the AI-based software and the hardware can be cost-effective and fit-for-purpose.

4. Discussion

We are led to believe that we are currently experiencing a new industrial revolution; one that will be data-driven, agile and autonomous (to use a few of the current buzzwords). One of the key ingredients in this revolution will be the need for fast, integrated metrology. However, many of the current metrology tools have hit fundamental and/or technical barriers that result in them being seen as a process overhead rather than potentially leading to innovative and commercial successes. Information-rich metrology is essentially a marriage of metrology with information technology and makes use of all the available information sources to enhance a given measurement scenario. We believe that IRM will allow many of the metrology barriers to be leap-frogged in the future and ease in integrated metrology as an essential part of any modern manufacturing process – not as an overhead, but as something that will enhance quality, enhance efficiency and ultimately, reduce costs. Lord Kelvin's statement from the start of the article basically says it all, but *just* measurement is often not enough. By making use of all the available information resources in our measurement and manufacturing processes, we can significantly enhance the way we make things.

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