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A single-click automated metrology demonstrator

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Abstract
During the past decade, additive manufacturing (AM) has grown from a promising but immature technology to a tool that is increasingly being accepted in manufacturing facilities around the globe. While researchers working in AM focussed on process optimisation, precision engineers dedicated time to research installing determinism and sustainability into a variety of areas within AM. At the University of Nottingham, we have developed a metrology demonstrator to showcase research that we have contributed over the last decade, pooling various aspects of our AM and precision manufacturing work into a single demonstration system. The vision behind this demonstrator is to create an open, reconfigurable measurement and characterisation platform, that remains live and active as research progresses over the coming years. The demonstrator is not a commercial product, but a rolling statement of the state of the art in automated metrology, showcasing measurement technologies.

In its first physical outline, the demonstrator comprises an open-source design, featuring photogrammetry and fringe projection measurement sensors, with the intention to integrate an additional surface texture measurement sensor in the future. The control software is designed to present a single-click, automated solution, capable of initially detecting the position and pose of a measured object using photogrammetry. Then, using a priori information (such as computer aided design data of the measured object or prior measurement data), the demonstrator automatically optimises a series of fringe projection measurement positions using artificial intelligence, reconfigures itself into multiple measurement poses and acquires data. Data is then passed through to a series of characterisation tools that perform specific measurements and evaluate their uncertainty. In this paper, we present the design and construction of, and initial results from the demonstrator system. Finally, we present a roadmap towards the next stage of development for the demonstrator, including an integrated approach to automated surface texture measurement.

Metrology; optical; co-ordinate; surface; fringe projection; photogrammetry; machine-learning

1. Introduction

Additive manufacturing (AM) has undergone rapid development over the past ten years, with significant improvements to AM technologies facilitating take-up of the technology within a series of high-value manufacturing industries, such as automotive, aerospace and medical. This growth has led to approximately a ten-fold increase in the global revenue of AM products and services, as reported by Wohlers Associates [1]. As AM is increasingly accepted, however, there is a similarly increased need for development of supporting engineering, not least metrology for AM, which has experienced a boom in research output over the past decade, covered extensively in several recent reviews [2–5].

One of the factors that the authors of these review papers identified as vital to the increased uptake of AM is a need for increasing determinism in AM. Similar conclusions were drawn by the authors of a metrology roadmap published in 2020 [6] and there has been a general push towards improving determinism in AM processes, including via the *euspen/ASPE Advancing Precision in Additive Manufacturing* conference. Particularly, development of measurement and characterisation capability is a part of the installation of determinism into AM. Sustainability is also an increasing concern in the precision and additive worlds, and new solutions are required to improve sustainable practices across industry.

There have been extensive developments across metrology for AM, and standardisation of measurement and characterisation protocol is beginning to achieve acceptance through the work of ISO technical committee 261 and many of its constituent joint groups. Good practice is also being developed, with the recent publication of *ASTM F3624-23 - Standard Guide for Additive Manufacturing of Metals - Powder Bed Fusion - Measurement and Characterization of Surface Texture* [7] representing an initial step in surface texture measurement and characterisation in the AM world. However, there is always more work to do, and new research continues in metrology for AM. Despite standardisation now being relatively forthcoming, work is generally published with the caveat that existing AM metrology solutions are often slow, complex and require extensive operator expertise to provide reliable results.

At the University of Nottingham, we have spent much of the last nine years creating AM metrology solutions geared towards instilling determinism, understanding uncertainty improving measurement speed, reducing costs or automating solutions. To date, these projects have been somewhat disparate and operating in isolation. In this paper, we present our recent efforts in creating an advanced metrology demonstrator, tying together many of our projects into a single system. This system is designed to be capable of optical co-ordinate and surface measurement of advanced components, such as AM parts, using an automated single-click measurement pipeline and relatively

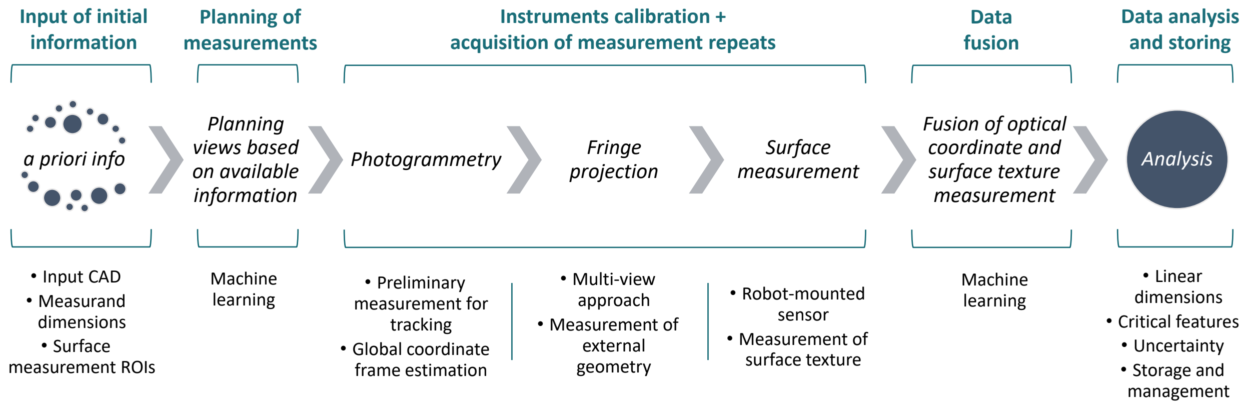

Figure 1. The software conceptual workflow comprising of five phases: input of initial information, planning of measurements, calibration of instruments and acquisition of measurement repeats; data fusion, and data analysis and storing.

cheap hardware. The goal is to create a fully autonomous, optimised measurement platform, capable of accepting digital models of parts and measurement requirements and automatically determining appropriate measurement strategies.

The proposed pipeline will be able to create a solution that requires minimal user input; leveraging machine learning and artificial intelligence to provide comprehensive measurement of desired measurands, including complete evaluation of task-specific measurement uncertainty. The demonstrator is currently a work in progress, and in this paper, we present its first draft alongside its design development, some initial measurement results and future steps towards the next stage of the demonstrator's construction.

2. Methodology

Given the variety of projects conducted in the Manufacturing Metrology Team at the University of Nottingham over the past nine years, the demonstrator is inherently somewhat Frankensteinian, but is designed in such a way as to represent something greater than the sum of its parts. The demonstrator's general construction is split into two areas, hardware and software, and designed in each instance to showcase the technology our team has created. In this section, we detail the planned software workflow and hardware specifications.

2.1. Measurement pipeline

The software pipeline is divided into five major phases, as shown in figure 1. The conceptual workflow features a) input of initial information, b) planning of measurements, c) instrument calibration and acquisition of measurement repeats, d) data fusion, and e) data analysis and storing.

Initial inputs include pre-existing knowledge of the measurand (i.e. computer aided design (CAD) model and extracted nominal dimensions) and knowledge of the measurement technologies employed. The planning of measurement before the actual data acquisition is performed using integrated machine learning algorithms, implemented for the optimisation of the next best scanning positions and repositioning of the measurement devices. Instrument calibration and acquisition of measurement repeats consists of the characterisation, initialisation and control of each measurement device (i.e. photogrammetry and fringe projection, see section 2.2) and the consequent acquisition and processing of measurement repeats (at least 3, 5 or 10 repeated measurements). Fusion of the multiple and heterogeneous datasets is performed using machine learning algorithms. The final stage consists of the analysis of the obtained results (i.e. analysis of dimensions, features, uncertainty evaluation, etc), management and storing of the relevant outputs. In addition, the software pipeline will implement mechanisms for monitoring and detection of drifts.

The software workflow starts with the input of the nominal CAD model and extracted nominal dimensions. The CAD reference geometry (in STL triangle mesh format) is fed into the software pipeline. The structure connectivity of the elements composing the triangle mesh (i.e. triangular facets) is analysed and relevant regions of the CAD surface are selected, indexed and stored. This procedure allows the determination of the best scanning views and camera positions for photogrammetry and the achievement of high measurement coverage. Once the photogrammetry datasets are processed, the resultant preliminary point cloud (i.e. a sparse point cloud) is registered within the same coordinate frame of the CAD model using machine learning (a procedure similar to the one showed in [8] will be implemented and optimised). Reference and exact positions for fringe projection measurements are computed, based on the photogrammetry measured points associated to the pre-indexed regions of the mesh. At this point, following the calibration of the instrument, the software initiates the measurement repeats obtained via the multi-view fringe projection sub-system (described in section 2.2). Feedback tools in the form of performance criteria (e.g. point count, point-to-point spacing, covered and uncovered surface, density in point-based sampling, dispersion of point-to-surface distances and related statistics – see [9]) are computed and the software is provided with indications of the measurement results, and can autonomously evaluate if additional measurement activities or adjustments are required. Eventually, we intend for a robot-mounted surface texture measurement device to perform measurements of pre-defined regions of interest (ROIs), though this sub-system is not currently implemented in the demonstrator. The datasets obtained from the input measurement sub-systems are fused via employing traditional fitting and registration methods. This fusion is performed to generate a single dataset including information from all input measurement sub-systems. An alternative route for data fusion based on machine learning solutions is also currently under development as a PhD project in the Manufacturing Metrology Team. The software workflow terminates with the analysis of the measurement results, including uncertainty evaluation.

2.2. Measurement hardware

The overall demonstrator is divided into six sub-systems that form the complete instrument: a fringe projection sub-system, a photogrammetry sub-system, a surface texture measurement sub-system, a part positioning sub-system, a control sub-system and the overall structure of the instrument. Some of these sub-

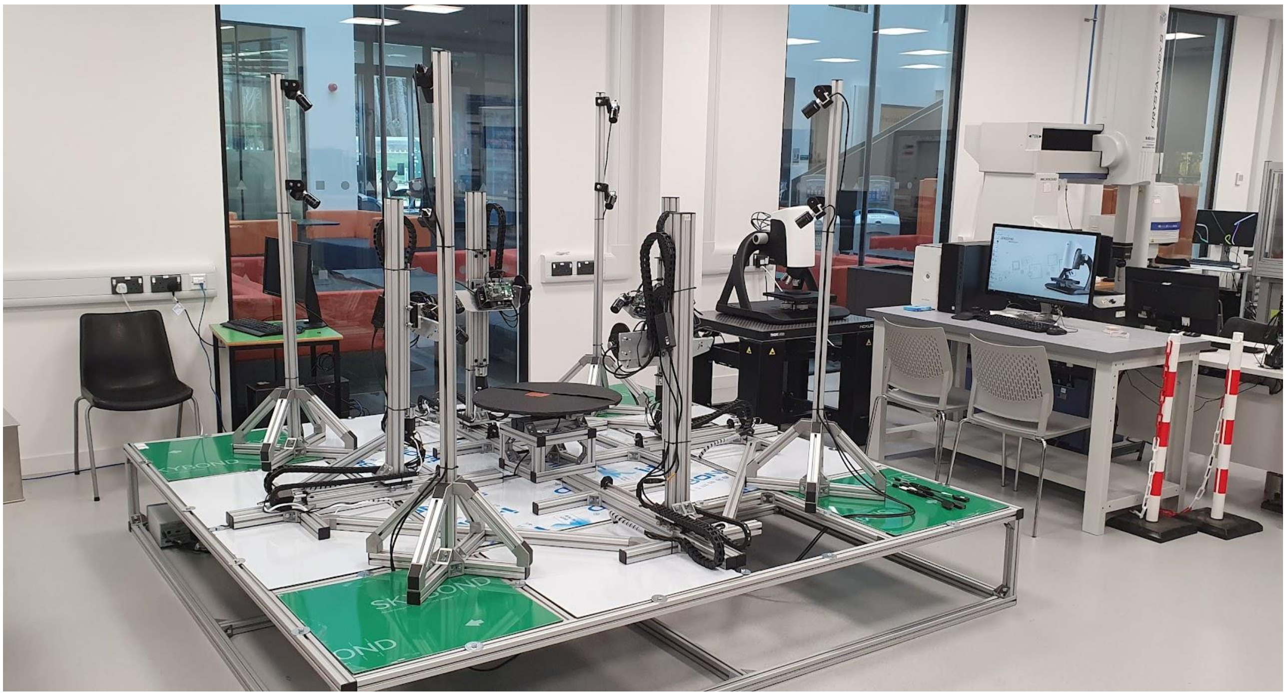

Figure 2. Photograph of the current MCDDM demonstrator set up, showing a central rotation platform surrounded by four fringe projection sub-sub-systems, each comprising a camera-projector pair and capable of three-axis motion (vertical, horizontal and radial). At the outer corners of the system, four photogrammetry pillars are shown, each featuring two photogrammetry cameras.

systems have been integrated into the system, while others are intended to be integrated in the future.

An image of the whole demonstrator, in its current state, is presented in figure 2. This figure shows the fringe projection sub-system, the photogrammetry sub-system, the part positioning sub-system and the overall structure of the instrument. The control sub-system exists underneath the main measurement platform, and we intend to integrate the surface texture measurement sub-system into a future iteration of the demonstrator. Figure 3 shows the first of the two co-ordinate measurement systems, the photogrammetry sub-system, featuring eight cameras, based on work published previously [8,10]. The photogrammetry system is used to, firstly, provide a coarse measurement and, secondly, to locate the computer-aided design data of the test part within the digital twin of the demonstrator system.

Figure 4 then shows part of the fringe projection sub-system, comprising four component fringe projection sub-sub-systems, also based on work published previously [11,12]. Each fringe projection sub-system sits on a three-axis motion stage, capable of positioning the individual sub-system at many positions relative to the part, which rests on a central rotation stage.

3. Preliminary results

While programming of the control systems and the operating software for the demonstrator is still very much an ongoing task and there remain some required refinements to the physical construction of the system, we are now able to present some early measurement data from the demonstrator.

In figure 5, we present some of this early data, acquired using the photogrammetry and fringe projection systems. We present this preliminary data with a caveat, however; it is intended to inform the reader of the system's potential for data acquisition but does not necessarily represent the final capabilities of the demonstrator. The software tools for automated performance evaluation are yet to be implemented, as is much of the automation of the system.

While implementation challenges remain, it is clear from figure 5 that the demonstrator is capable of producing the type of multi-sensor data described throughout this paper. Generation of various measurements from the point clouds shown in figure 5 and application of data evaluation metrics are then relatively straightforward using various commercial software packages and in-house code.

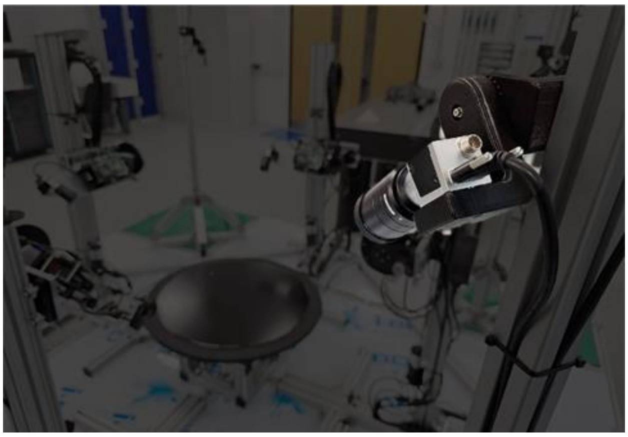

Figure 3. Highlighted photograph of one of eight machine vision cameras that form the demonstrator's "coarse" co-ordinate measurement system, mounted on a static post.

Figure 4. Highlighted photograph of one of fringe projection systems that form the demonstrator's "fine" co-ordinate measurement system, mounted on a three-axis (two linear, one rotation) motion system.

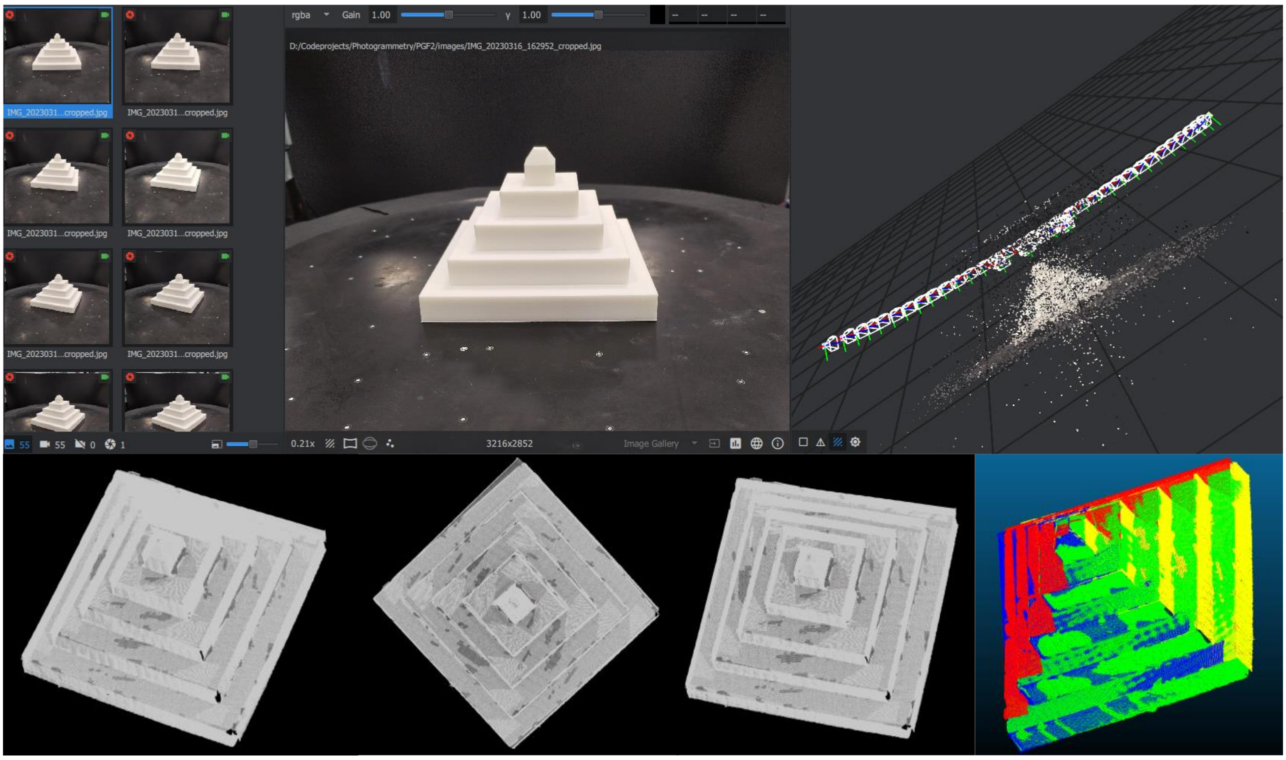

Figure 5. A preliminary 3D reconstruction created using Meshroom [13], from data captured using the photogrammetry sub-system (top); and preliminary 3D reconstructions created using Cloud Compare [14], from data captured, aligned and fused using the four components of the fringe projection sub-system and bespoke in-house Matlab [15] software (bottom).

4. Next steps

As noted in the previous section, the demonstrator is not yet complete. There is further work to do in its general physical and digital construction, primarily in refinements to the superstructure and the implementation of currently absent aspects of the operating software, respectively. The current goal for our team remains in completing this work, but several ongoing challenges remain beyond that point.

The first of these challenges is the task of fully open-sourcing the demonstrator technology. The demonstrator has always been intended as an open project, and we intend to publish all designs for the physical construction, as well as much of the operating software, where possible. We intend to conduct this open-sourcing activity via a public repository (or series of repositories), and we will do so once the first draft of the software is complete.

Once we have fully completed the first draft of the demonstrator, we intend to continue to iterate on the system through the inclusion of the outcomes of future projects created by our team at the University of Nottingham. We hope that the first of these additions will be the inclusion of surface texture measurement capability, as originally intended, using a surface texture measurement sub-system (using focus variation, coherence scanning interferometry or a hybrid of both technologies) mounted on a cobot. Implementation of such a sub-system will require extensive integration of surface texture characterisation software and represents a significantly sized project in and of itself.

Beyond the implementation of surface texture measurement capability, we intend to keep the demonstrator project alive as our team moves forward. With each new research project that current and future members of our team conducts, we hope to be able to integrate the outcomes into the demonstrator. The overarching goal is to create a system that is deliberately designed to be open source and reconfigurable, as required by the challenges of the day. Through the creation of an open and accessible measurement platform, we particularly hope to facilitate research into novel technologies, focussed on sustainable engineering. Ultimately, the system should never be complete and should continue to grow, as long as there is metrology research being conducted in our team.

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