Continuous in situ microstructure and composition analysis within 3D-printed structures using in-chamber sensors

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Executive Summary

The Additive manufacturing (AM) promises the capability of mass customisation: small-scale prototyping as well as larger-scale manufacture of functional parts where each item can still be flexibly adapted to the needs of a specific customer. Unlike traditional manufacture techniques such as injection molding however, the properties and hence economic value of objects created by AM can vary significantly from part to part as a function of the environmental conditions within an additive manufacturing system. There is therefore a significant economic justification for better understanding and control of AM processes.

This feasibility study investigated new methods for augmenting an AM system with lowcost sensors. The results of the feasibility study are a thoroughly-documented and replicable testbed for AM based on selective laser sintering, along with a new method for generating a per-build-layer sensor dataset that constitutes a form of birth certificate for each individual part produced by the AM process.

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Figure 1: Two examples of objects printed using our sensor-augmented nylon selective laser sintering testbed: a calibrated torque wrench and an ISO 527-2 mechanical test sample. The sequence of images in the third column shows the laser sintering for a single ~100µm layer as two torque wrenches are being manufactured. For each printed object, and for each ~100µm layer of the object during the AM process, our testbed produces a set of measurements including absorption spectra of the nylon powder that will be used in the layer. The testbed also provides, for each ~100µm layer, intake and exhaust air temperature and humidity from the print chamber, chamber vibrations, and more. The testbed will enable new research directions such as monitoring impurities in print powder per layer of a printed object, realtime adaptive control of SLS systems, and better prediction of properties of printed objects.
1. Research challenge

The mechanical and aesthetic properties of objects produced by nylon selective laser sintering (SLS) depend on the environmental conditions at the interface of the nylon powder as each of hundreds of layers is built up over the course of manufacture of an object. Better control of the properties of manufactured objects requires being able to quantify the conditions at the nylon powder surface as each of the layers of an object is created. Today, no easily accessible research tools exist for studying the surface microstructure and chemical properties and in-chamber properties within nylon SLS systems. This feasibility study investigated new methods for integrating low-cost sensors into a nylon SLS system and for acquiring per-layer measurements within the SLS build chamber. Our research hypothesis was that we could construct a reproducible research testbed for sensor-augmented SLS using existing consumer-grade sensors and that we could use this testbed to measure conditions within the build chamber as well as conditions at the raw and sintered nylon powder surface of the SLS process, for each of the hundreds or thousands of layers in a manufactured object.

2. Research challenge

Information about variations in materials composition during manufacture of an object would provide a unique fingerprint for each instance of a product. This information would enable more accurate estimation of product quality, would enable dynamic adaptation of the manufacture process to properties detected during manufacture, and more. This feasibility study investigated continuous in situ composition analysis within a nylon selective laser sintering (SLS) process. Our mission was to understand the process by which we could extend the traditional SLS chamber components with microstructure and materials composition sensors and in situ data analysis. The end results of the feasibility study are (1) a demonstrator for an SLS system, that, in addition to producing robust functional parts, provides, for each part produced, a detailed volumetric dataset of the variations in composition and microstructure throughout the layers of its construction; (2) new experimental results that show the viability of the system to produce per-layer near-infrared absorption spectra that are of comparable quality to direct sample measurement outside the chamber.

3. Approach

The major challenge in validating our research hypothesis was to find novel methods for using sensors that have a limited temperature operating range within the thermal conditions of the nylon SLS system. Our solutions to this challenge were to (1) physically extend the location of sensor signal transduction; (2) to use concepts from dimensional analysis to investigate new approaches to infer relationships between the different sensor modalities deployed within our testbed; (3) to investigate new approaches to creating virtual or synthetic sensors for properties that we cannot directly measure, using information on the units of measure of signals which we can measure, combined with information on the probability distribution of values those signals take on.

4. Implementation

We have made the design, assembly instructions, and associated sensor designs, and associated sensor firmware and print coordination software, publicly available [1]. Figure 2 shows a collage of pictures from our assembly of the first sensor-augmented SLS printer prototype.
Figure 2. Assembly process of our first instance of the sensor-augmented SLS system. We used as the basis for our system an SLS platform that comes in a kit of parts. Constructing a system from scratch rather than using a pre-built platform allowed us to have a thorough knowledge of the operation of the system.

Figure 3. Left: Warp, a multi-sensor platform we developed to enable our research. Middle: integration of the 248-band spectrometer into the SLS system. Right: We extended the optical path of the spectrometer to allow us to measure spectra at the powder surface without having to enclose the spectrometer inside the high-temperature build chamber.

Figure 4. Two glass optical fibers (yellow) attached to the SLS system blade feed light reflected from the powder bed into the two spectrometers. A third glass optical fiber (black) illuminates the powder bed with light from an external light source.
5. Results

The three key results of our feasibility study are: 1. A new open hardware platform (Sesame: An Open Sensor-Enhanced SLS Additive Manufacturing Platform) [1, 5] for research into sensing inside selective laser sintering of nylon, and Warp [2], a multi-sensor platform with a wide range of research experimental applications across sensing modalities. 2. A new method [3] for inferring equations that relate signals from multiple sensors as a potentially viable method to build analytic models of phenomena occurring inside complex multi-sensor systems such as the Sesame platform. 3. A new method for creating virtual or digitally-synthesised sensors [4].

Figure 5. The sensor-augmented SLS system consists of a Sintratec Kit selective laser sintering (SLS) system augmented with sensors: a 248-band near-infrared (NIR) spectrometer; a 6-band NIR or visible spectrum (swappable) spectrometer, both connected by glass optical fibers into the chamber; a Cambridge Warp hardware platform (a multi-sensor module); a Bosch CISS industrial sensor module. A PC runs a collection of software tools which read data from the spectrometer and other sensors. We have made both the documentation of the hardware modifications as well as the software open source.

Figure 6. The extension of the optical path of the spectrometer using a glass optical fiber does not significantly impair the quality of the absorption spectra we can measure inside the print chamber. The results show that the system can provide absorption spectra of quality similar to direct measurement of samples in direct contact with the spectrometer (i.e., without the optical fiber in the path).
6. Wider applications

The system we develop in this proof-of-concept will also have the potential to facilitate new cross-disciplinary research in computer vision applications in manufacturing. Today, researchers in the area of computer vision focus primarily on large-scale 3D reconstruction problems, such as reconstruction of living environments in indoor and outdoor navigation situations. The milliliter-scale challenges that our demonstrator will expose have the potential to generate many new exciting research directions in computer vision. This will be a valuable contribution to the already strong computer vision research in the UK, and will also be reciprocally beneficial for applications of computer vision in additive manufacturing.

7. Future Plans

The results of this feasibility study provides a foundation for our vision to investigate new kinds of Computation and Sensing Additive Materials (CSAMs) and provides a concrete basis for collaboration with other research groups.

8. Conclusions

Additive manufacturing promises the capability of small-scale prototyping as well as larger-scale manufacture of functional parts where each item can still be flexibly adapted to the needs of a specific customer. The results of this feasibility study are new experimental tools for research into studying the physical phenomena that occur during additive manufacturing processes based on selective laser sintering of nylon. Such new insight into the associated physical processes could lead to improved structural and aesthetic properties of objects produced.

9. References


10. Feasibility study team members

The study was conducted by a team of researchers from the University of Cambridge, Sheffield Hallam University and Imperial College London.

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