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Customized Smartness: A Survey on links between Additive Manufacturing and Sensor Integration

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Abstract

In many areas, Additive Manufacturing (AM) has made the decisive steps from prototyping to true manufacturing technology. AM processes excel based on aspects like outstanding geometrical flexibility and lack of tooling, which allows significant lead time reductions both in initial product design and in case of design adaptations. However, in production today, most of these advantages are realized based on homogeneous materials. Attempts at advancing the state of the art address the topic of material combinations and functionally graded materials. The challenges faced by such approaches differ in their level of severity, and are influenced in this respect by the actual AM process chosen. Beyond composites with spatially varying properties, the next level of complexity is the integration of geometrically defined 3D structures within the volume of a part, and specifically functional structures at that. Endeavours of the latter kind are currently receiving increased attention under headlines like “Structural Electronics” or “3D Electronics Printing”. Here, the surface or volume integrated structure typically is a sensor or electronic system. Beyond this system, the AM process then either provides a complex 3D substrate and thus addresses the packaging issue and/or replaces a conventional PCB, or it generates an engineering component directly and closely integrates it with electronic and sensor systems. So far, the backbone of most solutions realized have been hybrid production systems that integrate different manufacturing processes in a single piece of equipment. The present work provides a brief introduction to the various AM techniques and discusses a disambiguation based on their general capability of producing functional structures on a volume integration level. A classification of such structures is suggested that accounts for their level of complexity in relation to the typical, layer-wise manufacturing scheme adopted in AM. Examples stemming from a global research landscape are discussed in

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the context of this classification. In this, two special foci are selected reflecting related activities at the Fraunhofer Institute for Manufacturing Technology and Advanced Materials (Fraunhofer IFAM): One of these is a combination of manufacturing processes, with functional printing and other direct write techniques linked to AM processes in a dedicated manufacturing cell. The other addresses integration of pre-fabricated electronic components like RFID systems into metal components produced by means of selective laser melting (SLM).The study closes with an overview of future research trends towards producing components with integrated electronics. In doing so, special emphasis is given to AM techniques that allow for in-process switching of materials and thus have the potential of realizing complex systems not by combination of processes, but within the boundaries of a single process. Also addressed are potential application scenarios that profit specifically from the combination of AM and sensor integration.

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Keywords: Additive manufacturing; structural electronics; smart structures; sensor integration; 3D printing; smart products

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1. Introduction

1.1. AM processes - classification and overview

Additive Manufacturing (AM) is a primary shaping process defined by ASTM F2792-12a in a deliberate contrast to subtractive manufacturing as the “process of joining materials to make objects from 3D model data, usually layer upon layer” [1].

Nomenclature

AM	Additive Manufacturing
AMF	Additive Manufacturing File format
CBDM	Cloud-based Design and Manufacturing
FDM	Fused Deposition Modeling
FOS	Fibre-Optic Sensor
IDE	Inter-Digitated Electrode
IGES	Initial Graphics Exchange Specification
IoT	Internet of Things
LED	Light-Emitting Diode
LOM	Laminated Object Manufacture
MMP	Modular Manufacturing Platform
MWCNT	Multi-Wall Carbon Nanotubes
PCB	Printed Circuit Board
PLA	PolyLactic Acid, a thermoplastic polymer
PLM	Product Life Cycle Management
RFID	Radio-Frequency IDentification
SHM	Structural Health Monitoring
SLM	Selective Laser Melting
STEP	STandard for the Exchange of Product model data
STL	STereoLithography, also an AM file format
UAM	Ultrasonic Additive Manufacturing
UAV	Unmanned Aerial Vehicle
VRML	Virtual Reality Modeling Language

From a product design perspective, the layer-wise build-up of parts is the source of a geometrical flexibility and freedom of design unparalleled by other manufacturing processes. In AM, basically any volume element, be it internal or external with respect to the final part, is accessible to the process. This allows highly complex geometries to be manufactured, including e. g. designed inner structures, with the extra benefit of this complexity coming at next to no extra cost. AM thus in many cases becomes the only way of realizing e. g. intricate lightweight structure designs derived from topology optimization and similar approaches.

The typical AM workflow is depicted in Figure 1, which distinguishes between physical and digital models as staring point. While the former may e.g. stem from reverse engineering approaches, the latter represent the more common path in new product development. In short, this branch of the process starts with the definition of the 3D CAD model. This being finalized, the geometrical information contained in it is translated into an STL or similar file format representing the part surface by means of a triangle-based tessellation. Depending on the file format and the underlying process' capabilities, additional information like color and texture or, with some proprietary file formats, local material information, may also be included. Further data processing is needed for "slicing" the 3D model, now represented via its surfaces, to provide the layer-wise contour information that is mandatory for the building process. This is typically being done by machine-related software that furthermore adds manufacturing parameters like – taking the Selective Laser Melting or SLM process as an example – laser scanning pattern, speed and power and finally generates the G-code used in material control as output.

A major advantage of AM is that products may be conceived in an entirely digital manner until finally being submitted to a single production process. In practice, this limits the need to consider design for manufacturing requirements to those that apply for the AM process itself. Besides, it entails major lead time and cost reductions, since no tooling has to be designed and manufactured in parallel to the actual part.

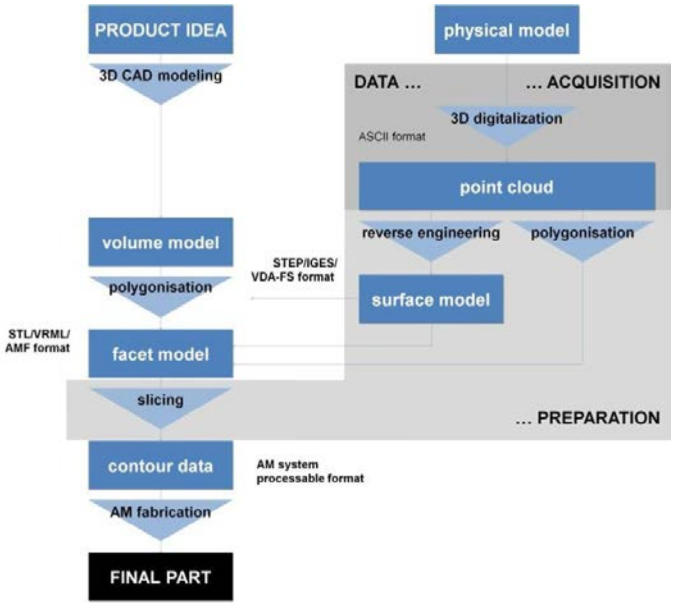

Fig. 1. Schematic representation of the typical AM work flow from digital part model to physical part, based on [2].

Originally, what is now called additive manufacturing, stressing its nature as a full-fledged, mature production process, has seen application in prototyping starting from the 1980ies already: Even today, rapid prototyping still provides first physical representations of new designs. The functionality of such prototypes has grown in parallel to the development of production processes and their accompanying coverage of a growing variety of materials. Thus where originally a mere design evaluation was targeted, functional prototypes have since become available that match or almost match the envisaged final product in terms of properties and performance in addition to outward appearance. A further development trend has adopted AM techniques not to produce the part directly, but the tools that are needed in conventional manufacturing processes. In this rapid tooling approach, the benefit introduced through AM techniques is at least threefold –lead time reduction leads to earlier availability of tools, if needs be, the flexibility of AM processes facilitates design changes, and finally, the wide range of geometries accessible to no other production methods allows for optimized tool designs that can e.g. enhance productivity. Conformal cooling channels in injection molding or extrusion tools are a prominent example of the latter kind (see Figure 2).

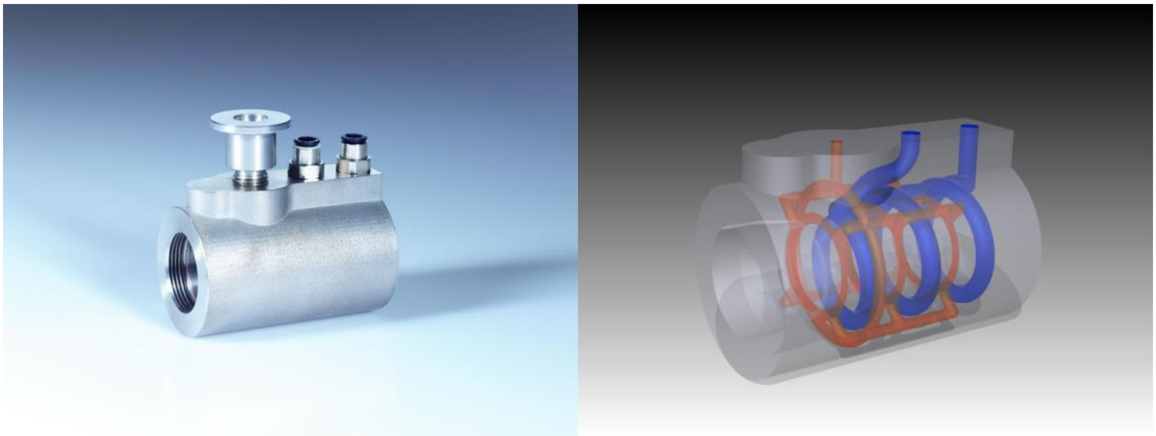

Fig. 2. Calibration tool for extrusion process with internal, conformal vacuum- and cooling channels (right, CAD model revealing inner structuring) – designs like this are inaccessible to conventional manufacturing processes [Image courtesy of Fraunhofer IFAM].

Table 1. AM process classes, descriptions and associated material classes (P = Polymers, M = Metals, C = Ceramics).

AM process class according to [1]	Process class description *Process examples*	Materials[1]
Binder jetting	Deposition of a bonding agent to join the matrix materials particles provided as a powder bed layer by layer. *3D Printing etc.*	Metals/M [6], Ceramics/C [7]
Directed Energy Deposition	Use of energy sources (e. g. Laser) to join particulate materials while feeding them through an orifice or nozzle. *Laser Engineered Net Shaping (LENS^{TM}), Direct Metal Deposition (DMD) etc.*	M [8], C [9]
Material Extrusion	Continuous extrusion of the matrix material through a nozzle, layer-wise deposition and subsequent solidification of same on the building platform. *Fused Deposition Modeling (FDM) or Fused Filament Fabrication (FFF), Robocasting, Freeze-form Extrusion Fabrication (FEF) etc.*	Polymers/P [10], M [11], C [12,13]
Material Jetting	Discontinuous, droplet-based deposition of materials. *PolyJet process, Direct Print Photopolymerization (DPP) etc.*	P [14,15], M [16], C [17]
Powder bed fusion	Use of energy sources (e. g. Laser, electron beam) to join particulate materials provided as a powder bed layer by layer. *Direct Metal Laser Sintering (DMLS), Selective Laser Sintering/Melting (SLS/M) etc.*	P [18], M [19,20], C [21]
Sheet lamination	Cutting-out of the cross-sectional geometry from a sheet-like material and bonding it as new layer to the preceding one. *Laminated Object Manufacture (LOM), Plate Diffusion Brazing (PDB), Ultrasonic Additive Manufacturing (UAM) etc.*	P [22], M [23,24], C [17]
Vat photo-polymerization	Point- or area-based layer-by-layer curing of a photopolymer in a vat. *Stereolithography (SLA), Direct Light Printing (DLP) etc.*	P [25], M [26], C [27]

[1] References are typically chosen to have review character for the respective field and cannot be assumed to cover it completely.

Since then, further developments in terms of process variants, process stability, material spectrum and enhanced material properties have fueled a partial transition towards direct part manufacturing – hence the general adoption of the term Additive Manufacturing. According to the widely recognized Wohlers report, the global market volume for AM was $4 billion in 2014, of which nearly 45% or $1.75 billion could be attributed to direct component manufacture. The same sources state a figure of $21 billion dollar as expected value for 2020 [3,4]. This optimistic perspective is underlined by a recent study investigating different product and production scenarios characterized by the particular expression of the three parameters customization, complexity and production volume and looking specifically at the potential of AM processes within the eight resulting major areas: In conclusion, based on aspects like complexity at no cost, low lead times and lack of tooling, except for the traditional mass manufacturing scenario described by extremely high production volume, low complexity and customization and high investment costs, Conner et al. find AM can reach economic viability in all these fields [5]. Since its first broader introduction in the 1980ies, AM has branched out into several different processes which cover the primary material groups polymers, metals and ceramics, as well as composite materials. A classification of processes distinguishing between the seven major categories listed in table 1 above has been offered by ASTM. Suitability of these processes for composite or graded material fabrication, and ultimately sensor integration differs and shall be discussed in the following sections.

1.2. Why sensor integration?

Several approaches for equipping a product with sensors exist. Most of these require some adaptation of sensor or sensor system to primary manufacturing process and service conditions, to make sure the system can survive the former and maintain functionality over a predefined period of time during the latter. Main issues in both respects are resilience in general and compatibility with host material characteristics [28,29]. Typically, the part production process, which in its expression in turn depends on the host material, constitutes the most crucial requirements towards the sensor system.

Table 2. Examples of applications scenarios for sensor and sensor system integration.

Application scenario classification	Scenario description *Primary part production process (examples)*	Type of sensor *Host material*	Ref.
Anti-counterfeiting	Secure identification of objects, e. g. as countermeasure against plagiarism. *light metal casting (high pressure die casting/HPDC)*	RFID *Al alloy*	[39,40]
Object tracking	Tracking and localization of objects in production logistics, operating theatre etc. *light metal casting (HPDC), selective laser melting*	RFID *Al alloy, EOS IN718 Ni alloy*	[41,42]
Vibration damping	Monitoring and control of structural vibrations through material-embedded piezoelectric modules. *light metal casting (HPDC)*	piezoel. sensor/actuator *Al alloy*	[43,44]
Structural Health Monitoring	Damage detection/localization/classification up to remaining lifetime prediction in aerospace applications. *Resin transfer moulding (RTM)*	fibre optical sensors *CFRP*	[45]
Fly-by-feel	Sensitized airfoil supporting autonomous flight. *composite lamination techniques (envisaged)*	e. g. strain gauges, piezoelectric sensors *CFRP (envisaged)*	[46,47]
Production process monitoring	Material-integrated sensors to monitor curing processes. *Resin transfer moulding (RTM)*	dielectric IDE *CFRP*	[32]
Robotic tactile sensing	Increased dexterity in robot manipulation, enhanced and safer interaction e.g. with humans. *part production processes match sensor system production processes as the sensor system and substrate is the e-skin*	PVDF piezoelectric sensors *PVDF carrier film, PDMS top layer*	[48-50]
Advanced user interfaces	Sensitive materials and surfaces as means for object-user or human-computer interaction. *diverse (abstract concepts discussed)*	e. g. mechanical, thermal sensors *diverse*	[51,52]

Motivation for sensor integration naturally depends on the application scenario towards which an engineering component is developed. A sensor network physically linked to a specific product can form an essential part of its functionality, for example through serving as user interface. Furthermore, it can be applied to monitor production process and/or service life, the latter e. g. in SHM or PLM scenarios [30-32]. To date, several conceptual discussions of sensor-integrated materials have been published [33-36]. A further extension of capabilities is achieved when actuation is added – here, shape or property change can support structural of functional performance [37,38]. Table 2 lists these and further, exemplary case studies that incorporate product-integrated sensors, sensor networks and systems enabling specific, advanced functionalities and classifies them via the associated, generalized application scenario. Most of these examples achieve sensor integration through conventional manufacturing techniques. At the same time, however, several of them are linked to areas of applications like aerospace in which AM has gained a strong footing in recent years.

1.3. Linking Additive Manufacturing and sensor integration

Having briefly outlined both the AM and the sensor integration landscape, the question remains which best of both worlds we expect from connecting them?

The answer is manifold. First of all, as is underlined by the market figures cited above, we expect AM in general to gain on other production processes – thus if we assume, e. g. in an IoT context, products becoming smarter and smarter anyway, we must have solutions that allow us to realize this smartness on an AM foundation, too. Besides, if we consider volume integration with its many advantages, we have to concede that there are few processes that lend themselves as easily as AM to this approach: Thanks to the sequential, layer-by-layer build-up of parts, on a matter of principle, AM offers full access to the inside of whatever is fabricated. Finally, some research trends in production engineering suggest that the re-shuffling of value chains anticipated in new paradigms like Cloud-based Design and Manufacturing (CBDM) fits extremely well with many aspects of AM – for example, AM's almost complete lack of lead times and the (at least theoretically) facile possibility of digitally transferring a complete set of ready-to-use manufacturing information. Combining these features could help establish a cloud-based manufacturing-as-a-service environment in which customers and service providers would be networked e. g. via automated quotation tools [53]. Sensor integration would add availability of usage-data. In a long-term projection of the scenario, gathering and evaluating life-cycle information could be applied to implement a continuous product optimization process [54]. Besides the integration of sensors, the primary prerequisite for this constant evolution to be economically viable is a manufacturing process that offers utmost flexibility - like AM. Scenarios that integrate AM in this sense can in principle go beyond alternative, product generation-oriented discrete optimization procedures [55,56].

In view of such considerable application potentials, the present text takes up the aforementioned fundamental development trends and investigates, in section 2, the current state of their interrelation and combination in terms of AM-based or –associated manufacturing concepts, processes, products and product ideas. In doing so, as a first step, a classification of integration strategies is attempted that reflects the specific nature of AM processes. In the following section 3, four concrete examples have been selected which stand for as many different approaches and serve to highlight their specific aspects and boundary conditions. Prior to the conclusion, future trends in the combined field of sensor integration and additive manufacturing are discussed and research needs inferred from these in section 4.

2. Sensor and electronics integration in Additive Manufacturing: Overview

Sensor and/or electronics integration in AM processes must address several challenges: Chang et al. summarize the main issues as follows [57]:

- limited surface and thus substrate quality achievable by AM processes without post-processing
- compatibility of material properties and mandatory thermal processing (example given by Chang et al. is sintering of conductive inks on polymeric substrates, functional material stability at metal or ceramic AM part sintering conditions could be another)

- in case of functional structure integration on building planes, the need to suspend the volume building process during deposition of the functional material for an extended period of time, with potential negative effects on inter-layer connectivity and strength

While these may be the main difficulties encountered, there are further points of concern besides them:

- multi-material nature of sensor/electronics-integrated AM parts and the ensuing need to cope with deviations in processing characteristics among different functional and structural materials
- difficulty of practically realizing full spatial freedom due to the layer-wise build-up of parts, which hampers cross-layer integration

Against this background, it is not surprising that several different approaches towards the aim of smart AM parts are being evaluated. The following section provides an overview of studies on sensor integration in parts produced via AM processes. The main separating feature in this respect is the position of the sensor with respect to surface or volume of the part. In this context, we distinguish between surface application and surface integration. We define surface application as a method in the course of which a sensor or sensor system manufactured in an entirely separate production process or process chain and is bonded to the surface of the AM component subsequent to the latter's main production steps. In contrast, we consider as surface integration a methodology which establishes not only the mechanical connection between sensor system and the AM part as substrate, but at least part of the sensor system itself in situ. To give an example, while adhesively bonding a conventional strain gauge to the outer surface of an AM part would figure as sensor application, and will thus not be considered here, Aerosol Jet^{TM} printing of a strain gauge at the same location is considered sensor integration and will consequently feature in table 3[58,59]. In terms of volume integration, the practical boundary conditions of AM processes make it reasonable to distinguish between internal sensors and sensor systems that are restricted in their placement to the actual AM building planes and others which are not, but can effectively cross these planes at least on the most simple level of cross-plane interconnects. The reader should note that processes capable of the higher levels of complexity can typically also handle the corresponding lower ones - in table 3, they will appear in the field representing their highest capabilities.

The secondary, column-wise classification besides integration level is essentially based on the practical realization of the smart components: Has it been made via an extended process chain that involves transfer between different manufacturing systems and tools ("separate"), has it been made using a single manufacturing system that integrates different processes ("hybrid"), or has a particular process been used with sufficient flexibility to produce the structural as well as the functional components of the final part ("single process")? For each class that has seen practical realization, though not necessarily in a commercial setting yet, table 3 names the respective approach and provides a reference. The focus in this respect is on processes, not on materials or applications. Selected approaches are explained in more detail in section 3 below, which contains four such case studies. With these considerations in mind, we can define the main sensor integration categories summarized in table 3 below.

Not surprisingly, a closer scrutiny of the above processes reveals that for one thing many address specific subtopics rather than providing complete solutions for structural electronics systems. Besides, the majority of the suggested methodologies is dedicated to polymeric parts, the reason being, among others, the more benign processing conditions, i.e. primarily the lower thermal loads encountered, a boundary condition which also favours surface over volume integration in those cases that actually address metallic or ceramic materials. Furthermore, if highly performant electronics systems are to be integrated, this is invariably done through automated or manual placement of separately produced, conventional electronic devices (see e.g. [41,65,70]): Currently no direct write or similar method is available that could generate these in situ, at least not at anything near to competitive performance levels. For a similar reason, even for polymer parts specific processes have been suggested which produce the sensor in a separate step, then use a transfer approach to integrate it e.g. on the building plane of the AM part. An example in this respect is the study by Chang et al., which answers concerns regarding both sensor and part performance by producing both in largely separate environments and thus in each case under conditions nearer to the respective optimum [57].

As a general remark, it must be understood that none of the approaches discussed here can be termed the best. Instead, in each case, selection of a suitable manufacturing route has to consider the technological and economic requirements of the application in question. To give an example, single process solutions may benefit production scenarios that do not require highest levels of performance but profit from facile product design adaption. A single production processes which only affords the suitable materials and can otherwise rely on an entirely digital implementation of design changes will deliver the required flexibility. However, the need to match all materials to common processing conditions may introduce performance deductions. In contrast, hybrid multi-process solutions will raise investment costs and system complexity and may thus compromise cost-effectiveness. In this respect, the modular manufacturing platform's concept can be considered a compromise, since its modularity may facilitate tailoring to individual products, specifically since modules can be easily added and removed following e.g. a leasing model.

Table 3. Categories describing sensor integration in AM and examples of their implementation. Highlighted fields in the table are presented in more detail in section 3.

Level of integration	Manufacturing system configuration		
	separate	hybrid	single process
Surface integration	Aerosol Jet^{TM} printing of conductive paths for LEDs and motors of a small UAV produced via FDM [60].		
	Case study 1: Fraunhofer IFAM modular manufacturing platform [61], for details see section 3.1.[1]		
Volume integration			
2D system on building planes	Screen printing of insulating layers on Al foil for joining via UAM as LOM variant [62].		
	Embedding of optical sensor fibres in 1000/3000 series Al alloys via UAM [63].		
	Transfer of Aerosol Jet^{TM} printed sensors to building planes of PolyJet type AM part [57].		
2D system connected across building planes	3D and cross-plane vias el. interconnects in a 3DP ceramic part, conductivity via electro-less copper plating [64].	FDM combined w. inkjet printing commercially available through Voxel8. Ink-jet printing of conductive paths etc. plus manual pick-and-place [65,66].	
	Addition of surface mounted electr. components on ceramic parts with cross-plane interconnects [64].	Encapsulated copper wire and copper mesh capacitive sensing for 3D printing applications [67].	
3D system	**Case study 2:** RFID integration [41], see section 3.2.	Dispensing of liquid to paste-like materials incl. filled functional (conductive) variants allowing fast switching of cartridges, combined with FDM system for processing of polymers and low-melting metal alloys – typically, FDM is employed for structural part components, which would make this a hybrid approach [68-Mal, 69-Mal].	
		Case study 3: Hybrid system incl. FDM, ink dispensing, thermal embedding of wires, micromachining, robotic pick & place etc. for "single setup" realization of smart objects [70], see section 3.3.	**Case study 4:** Direct Print Photopolymerization (DPP) process using photopolymer-based inks functionalized by additives and printheads allowing in-process switching of inks for 3D material control [71,72], see section 3.4.

[1] In conjunction with an interrupted AM process, the modular manufacturing platform can also be seen as example of 2D volume integration on building planes.

3. Selected case studies

3.1. Flexibility throughout: A modular manufacturing platform for printed sensor surface integration on AM parts

Surface integration of printed sensors on additively manufactured parts must be able to cope with the specific characteristics of the latter, notably surface quality and typically non-planar surfaces. To meet these requirements, a modular manufacturing platform (MMP) has been realized which integrates handling techniques for transfer of workpieces between several characterization, functionalization and post-processing modules which in combination allow providing arbitrarily-shaped AM parts with a large variety of functional elements [73].

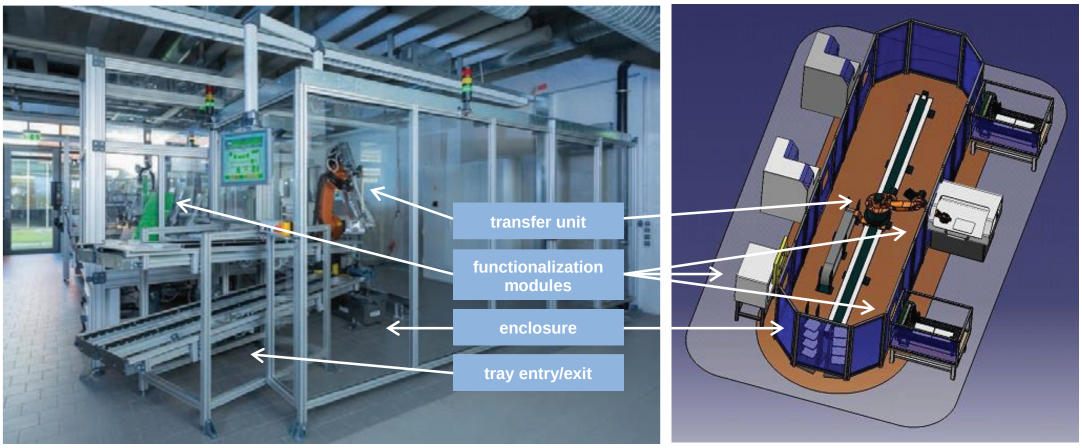

Fig. 3. A modular manufacturing platform designed for part functionalization through surface integration of sensors on arbitrary, including non-planar surfaces, targeting sensor integration for AM parts: Photograph of installation at Fraunhofer IFAM and CAD model highlighting the modular setup and the robot-based concept of inter-module workpiece transfer [Images courtesy of Fraunhofer IFAM].

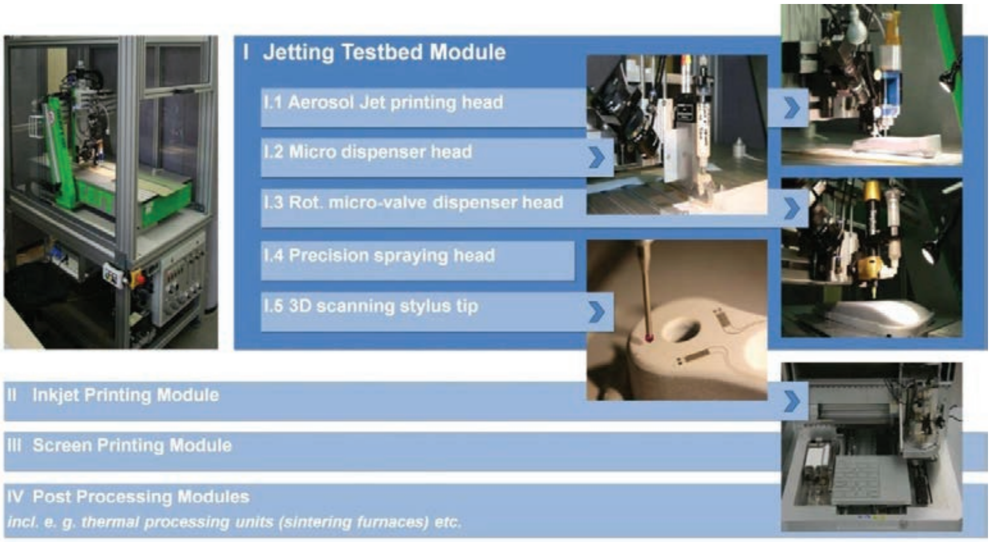

Fig. 4. Functionalization, characterization and post-processing modules incorporated in the MMP [Images courtesy of Fraunhofer IFAM].

The major characteristic of this manufacturing cell is its outstanding flexibility. Figure 3 depicts the real system as well as its schematic setup, illustrating the various modules linked to each other through the industrial robot which serves as a transfer unit, utilizing specifically designed workpiece carriers adapted to the processing modules. The latter are represented in Figure 4.

Three main functionalization modules integrate the capabilities of the modular manufacturing platform in terms of in situ creation of sensors and basic electronic structures on part surfaces. These are the jetting testbed module (JTM), the inkjet printing module (IPM) and the screen printing module (SPM). Among them, the jetting testbed allows exchange of tools and thus covers not only the 3D characterization of workpieces via a stylus tip, but also a variety of further direct write techniques – namely aerosol jet printing, micro-dispensing, rotary micro-valve dispensing and spraying. Table 4 details the functionalization processes in terms of choice of materials and achievable geometric characteristics (feature size, resolution etc.).

Control of the modular manufacturing platform is currently realized on a partially coupled level in which transfer and processing systems can identify part transfer trays based on pin coding. The robotic transfer unit itself can receive feedback from the individual processing modules whenever they are either ready to receive a new component/tray, or have completed a processing step and can thus be relieved of the current one. The individual functionalization units, on the other hand, have to be programmed separately and will perform their respective task not based on identification of the incoming component and association of processing needs, but simply by executing their currently active programming. For a research environment, this setup offers the indispensable flexibility. For a directly derived production scenario, updates e. g. allowing parallel processing of multiple parts/trays could easily be implemented.

Table 4. Functionalization processes integrated in the modular manufacturing platform and their main characteristics.

Functionalization process	Module	Description	3D capability (qualitative)	Resolution (typical range) [µm]
Aerosol Jet^{TM} printing	JTM	Optomec Inc., Albuquerque, USA, aerosol jet printhead.	+[1]	10-100
Micro-dispensing	JTM	Vermes Microdispensing GmbH MDS 3000	+[1]	100-1000
Rotary micro-valve dispensing	JTM	Techcon Systems, used for deposition of higher viscosity materials in contact with the substrate.	+[1]	100-1000
Precision spraying valve	JTM	Techcon Systems, used for homogeneous surface coatings incl. coverage of larger areas.	+[1]	n. a. area-based
3D scanning	JTM	Stylus tip-based geometry/topography capture, used in track planning for direct write surface functionalization. Accuracy (repeat) 15 µm, max. positioning fault < 8 µm.	+[1]	3 µm measuring
Inkjet printing	IPM	Inkjet printing module with variable printheads	○	40-200
Screen printing	SPM	Screen printing module suitable for structured and area coating.	-/○[2]	40 → area coating

[1] Determined by current 3-axis JTM setup, ind. processes allow even better (++) 3D capability.

[2] Special device integrated for printing on rotationally symmetric surfaces (via part rotation) available.

Figure 5 depicts a product example which has been realized by means of the modular manufacturing platform: The structural elements of this leg prosthesis shaft have been produced via the FDM process from PLA, a thermoplastic polymer. Its functionalization relies on a surface-integrated strain gauge realized via Aerosol Jet^{TM} printing. The conductive paths that lead across the part as well as the contact pads at their end were deposited through micro-dispensing. The material of the resistive sensor is a silver based ink, while interconnects and contact pads are made from silver particle-filled epoxy. Material and associated process selection have to account for the relatively low thermal stability of the PLA substrate. For this reason, the necessary consolidation of the silver ink is done via UV photonic sintering [75,76], while the filled epoxy is thermally cured at sustainable temperatures below 100 °C.

Fig. 5. Leg prosthesis part produced from PLA via FDM showing complex non-planar surfaces, with surface-integrated strain gauge sensors produced by Aerosol Jet^{TM} printing and conductive paths deposited via micro-dispensing, both using the modular manufacturing platform [74].

Approaches similar to the aforementioned modular manufacturing platform are investigated by a number of other research groups, including e.g. KU Leuven, where the focus is specifically on application of the Aerosol Jet^{TM} process for functionalization of AM parts [77]. In comparison to these, the Fraunhofer approach excels in terms of the large number of processes it incorporates and its modularity, which allows facile translation of the present research, process verification and demonstration environment into an actual production system with reduced, application-oriented scope which can still easily be adapted to newly emerging needs. As a research tool, an added value of the MMP is its high level of reproducibility in the coupling of different processes.

3.2. Let them talk: The why and how of RFID tags integrated into AM components

RFID volume integration may serve several purposes – the technology can be used to access sensor information, it may support protection against plagiarism and product counterfeiting by providing products with a unique, hard to manipulate identification which may also be used in autonomous control of production and related logistic processes [39,42,78], and it may help in detecting and localizing objects in general [40,42]. In the latter role, the technique has been studied in view of medical applications ([41], see Fig. 6), which in general are an attractive field for AM due to complexity of parts and a frequent need for personalization and thus low production volumes [54,79], as already the previous application example has illustrated.

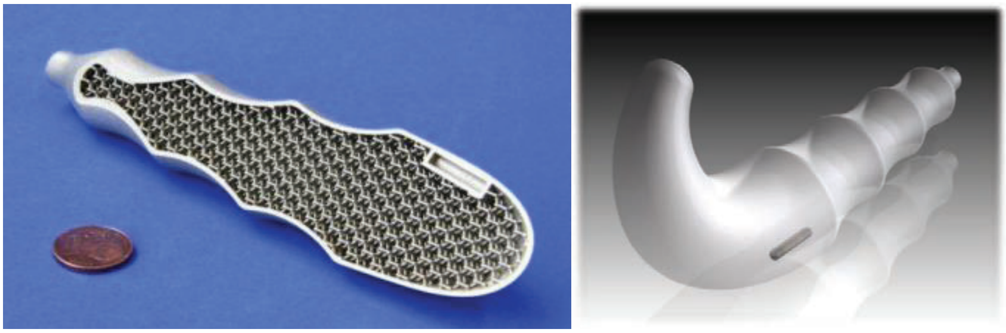

Fig. 6. Example of a metallic AM part (lightweight surgical handle) with internal structuring and provisions for near-surface volume integration of an RFID transponder (Image courtesy of Fraunhofer IFAM, see also [80]).

RFID tags represent comparatively complex electronic systems which up to now cannot be integrated with an AM part via *in situ* processes, specifically not in a metallic part. Thus in the studies discussed here, which rely on selective laser melting as production technique, integration is based on entirely separate production of the RFID system. During part build-up, a cavity suitable for taking up the RFID tag is left out. Once this pocket has reached a suitable size, the RFID tag is inserted. Prior to this, the powder that has accumulated in the cavity has to be partly removed. Closing of the cavity has to be postponed until the powder layer above the RFID is thick enough to allow melting the top layer without affecting the RFID system's functionality. Due to the shielding effect of a metallic environment, readout of the RFID tag is possible only at cover layer thicknesses below a certain margin, the value of which is determined by interrogation frequency and material itself. Experiments on IN718 Ni alloy SLM parts have confirmed theoretical considerations that low frequencies allow deeper penetration. In practice, at a distance (read range) of 7 mm from the part surface, the maximum permissible thickness of the metal layer covering the RFID was found to be 1.7 mm at 125 kHz. Theoretical considerations taking into account frequency, material and relative permittivity had suggested a penetration depth of 1.59 mm at this frequency compared to no more than 0.15 mm at 13.56 MHz [41].

For deeply embedded volume-integrated sensors in metallic parts, readout of data will thus always be a problem unless conductive paths can be integrated that lead out of the part. This can in principle be done in the same way as for the RFID itself, however, the limitation that goes with this approach is that neither the conductive paths nor the integrated electronic system will be physically attached to the part itself. For an RFID tag that solely serves as identification, this is fully acceptable. For a sensor that is meant to tap information from the product it is embedded in, it may be unsuitable, specifically if measurands are of mechanical type. For temperature measurements, response times may be lowered due to imperfect or even variable thermal contact.

Besides, concepts in which integrated conductive paths cross the building layers are, though not impossible, in any case hard to realize and require specific attention to be paid to the build-up sequence, which should ideally create the cavity for the conductive path first, followed by the cavity for the electronic system, the insertion of the interconnect, its electrical connection to the electronic system, the positioning of the latter in the cavity and finally the closure of this cavity.

3.3. Integrate whatever you need: A manufacturing system covering processes from AM to direct write and beyond

Similar to the concept of the modular manufacturing platform in its approach of combining several processes to achieve utmost flexibility in sensor integration, but not limited to the exterior of AM parts thanks to the integration of the AM process itself, are manufacturing system concepts brought forward by the University of Texas at El Paso, UTEP [70]. One example of these, the multi^{3D} system described together with product examples by Espalin et al. [70], comprises a large variety of structure build-up, material deposition and integration processes, namely

- FDM (two separate systems),
- micromachining,
- precision dispensing and
- wire embedding.

Added to these options are handling devices which allow pick-and-place operations for integration of separately produced functional units like energy storage (batteries, supercaps) or silicon microelectronics devices. The system possesses a custom, LabVIEW-based control which links the various integrated processes - except for, at the state published in 2014 [70], component placement - and thus allows the direct submission of build jobs for complete, combined structural and electronic systems in three dimensions. Future development goals foresee the integration of additional processes like laser ablation or inkjet printing to further extend the scope of possible products.

When seen as a manufacturing system, the close inter-process coupling and the possibility of completely defining a part in terms of its electronic, functional and structural features makes this solution attractive for fast realization of geometrically complex 3D electronics that lie within the framework of the processes implemented. It is worth mentioning in this context that currently, choice of the latter is not so much focused on in situ realization of functional units, but more on interconnecting separately-produced components, which might seem to challenge the association to the hybrid system configuration class in table 3. Specifically the planned embedding of inkjet printing, however, is likely to shift the balance in the opposite direction again. True production systems are likely to be tailored more closely to an envisaged task, and might therefore gather a more select set of processes only, in order to e. g. limit idle time of subsystems. In this respect, the approach is similar to the modular manufacturing platform described in section 3.1.

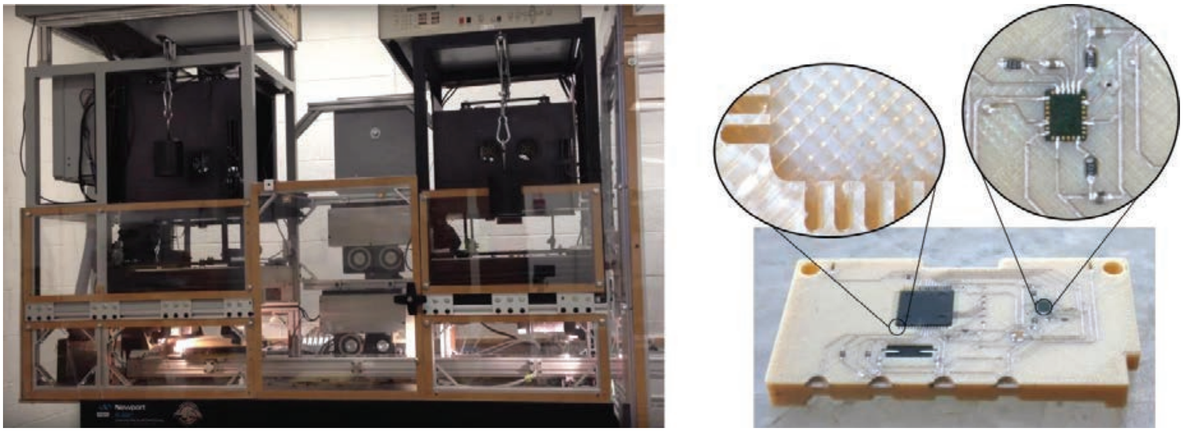

Fig. 7. Multi-process manufacturing system for the direct production of sensor and electronics-integrated smart products and/or structural electronics components as developed at the University of Texas at El Paso (UTEP) (left) and sample part manufactured using this setup and highlighting micromachined features and integrated silicon microelectronics component (images by courtesy of W.M. Keck Center for 3D Innovation, University of Texas at El Paso, Texas, USA).

3.4. Doing it all in one go: Direct production of structural electronics parts in a single process

A subgroup of the material jetting class processes basically relies on inkjet printing of polymer-based materials that are photo-curable. This allows immediate solidification after printing using e. g. UV light. Examples of these methods include the PolyJet [81] and the Direct Print Photopolymerization (DPP) process [82]. These processes offer a certain amount of flexibility when it comes to building multi-material structures. Stratasys Ltd., for example, offers the Digital Materials concept for their respective devices, which allows controlled combination of certain base resins during printing to achieve a scope of tailored material properties. The materials offered on a commercial basis are usually of structural material type and either offer specific property profiles (e. g. rubber-like materials with tunable Shore hardness), or secondary properties like transparency. Apparently still missing in the portfolio, however, are functional materials [83]. In contrast, the DPP process has specifically been adapted, on research level, to realize functional materials. Since here, too, a photopolymer must guarantee processability, functional material properties are typically achieved through dedicated additives. Table 5 lists published examples of such formulations, relating the application, i.e. the type of device realized, and the actual material formulation.

In the context of the information collected in Table 3, geometrically fully flexible volume integration in a single process has been described as the high road towards sensor integration. Currently, material jetting of polymers appears to be the nearest approximation to this vision that is currently available: The combination of high resolution, controlled material deposition with the possibility of photo polymerization, which allows immediate solidification of the material after printing and thus facilitates deposition of materials with different functional or structural roles directly besides each other, provides the foundation for effectively printing a structural electronics system directly. This assessment is further supported by the fact that multi-material/ink print heads are naturally state of the art. The technological basis for multi-material deposition is thus fully available. Besides, since inkjet printing has been used for a considerable time already as a direct write technology for realizing various kinds of sensors, interconnects etc. [58,59,85,86], many material formulations usable for this purpose are already available and tested and in principle only need to be transferred to PolyJet, DPP and the related processes. Nevertheless, to the authors' knowledge, no true "single process" solution that fully integrates these capabilities has yet been reported.

Table 5. Selected examples of functional material formulations processed via DPP, PolyJet and related processes.

Device/Functionality *Process*	Material formulation	Ref.
Conformal circuitry *DPP*	CNT/polymer nanocomposite: MWCNT blended with ethoxylated bisphenol A dimethacrylate containing 3 wt.% of 2,2-dimethoxy-2-phenylacetophonene (DPMA) as photoinitiator	[82]
Tactile sensor *micro-dispensing and curing*	CNT/polymer nanocomposite: MWCNT blended with cyclic trimethylolpropane formal acrylate containing 3 wt.% of 2,2-dimethoxy-2-phenylacetophonene (DPMA) as photoinitiator	[72]
Resistors *direct print/cure micro-dispensing*	CNT/polymer nanocomposite: MWCNT blended with cyclic trimethylolpropane formal acrylate containing 3 wt.% of 2,2-dimethoxy-2-phenylacetophonene (DPMA) as photoinitiator and 2 wt.-% of 2,2'-Azobis(2-methylpropionitrile) as thermal initiator	[84]

One reason for this apparent gap may be the fact the aforementioned fact that usually, the geometrical design freedom may come at a cost: For one thing, in DPP and PolyJet processing, all functional material formulations must base on photopolymers, or combinations of curable polymers with photoinitiators as additives. These constraints in the choice of materials imposed by the need to facilitate processing may in principle compromise performance e. g. of dedicated functional materials. Similar effects have been observed in other cases, too, where a balancing between processability and properties is necessary. A good example in this respect is the copper wire embedding process developed by Wicker et al. in view of the limited electrical conductivities of both inkjet-printed and micro-dispensed interconnects [87].

4. Looking ahead: Future research directions

As both the overview of the state of the art and the case studies show, several challenges remain when it comes to sensor integration in AM. At the same time, it is obvious that in a world of products that differ in production volume, complexity, safety, reliability and durability requirements as well as customization and functionalization needs, there is no single answer to the question of what might be the best solution. Nevertheless it is possible to identify promising research directions, and especially where low production volume meets customization and/or complexity requirements, AM will come into its own.

On a technological level, one of the major issues is increasing flexibility in terms of the integration options. Hybrid manufacturing systems as e. g. brought forward by UTEP in several studies [70,88] constitute a considerable effort in terms of machine design and build-up. In contrast, methods that can process both functional as well as structural materials and easily switch between them provide significant advantages in terms of process complexity, but also with respect to productivity, as they get by without extended non-productive times otherwise needed for transferring the workpiece from one processing module to the next. From this perspective, direct write processes usually applied to sensor production/structuring/deposition like inkjet or aerosol jet printing move into the focus, since for them, various functional materials are readily available already today.

Perhaps even more important in this respect is the fact that for both the aforementioned methods, related developments exist which, as AM processes, allow production of 3D parts rather than 2D or 2.5D structures that depend on some kind of substrate. These include the PolyJet and DPP process essentially based on inkjet printing for polymeric materials and the LENS^{TM} process [89], a development from Aerosol Jet^{TM} printing, for metals and ceramics: A prerequisite for single-process sensor integration is a part consolidation method that involves feeding the material to the actual location at which it is joined to the previously-built portion of the part, a feature which clearly distinguishes the aforementioned methods. PolyJet and DPP achieve this via photo polymerization, while LENS^{TM} uses laser energy to fuse the material as it is fed to the building spot. For these processes, the optimization of existing and the development of further functional materials to enable new kinds of devices remains a vast playground for research with a considerable application and commercialization potential.

Thus from a perspective favoring single process solutions, in terms of AM process classes, material jetting, material extrusion and directed energy deposition (see table 1 for process descriptions) must seem best suited for sensor integration, and less so processes that work with a bulk of material like powder bed fusion or vat photo polymerization. Binder jetting processes take an intermediate position in this respect since they allow modification of the powder bed via the locally injected binder phase [90].

This said, another distinction has to be made regarding metal- and polymer-based processes: The latter allow integration of functional materials as composites using a polymer matrix. This way the processing temperatures of the functional component are within the same range as those of the polymeric structural components. Besides, metal matrices usually require an insulating layer surrounding functional and/or simple conductive structures, whereas polymeric materials can dispense with this further interlayer due to their typically dielectric nature. Having to add another component once more complicates the quest for material combinations sufficiently well matched in terms of processing characteristics and in-service behavior and thus adds a new entry to the list of research needs.

5. Summary and Conclusion

As AM enters the arena of competitive production processes, constantly widening the scope of its economic viability based on a still highly dynamic evolution of processes, it meets with matching trends in sensor and electronics integration. Today, first examples of directly printed smart products exist. These, however, still afford a combination of several production processes which is otherwise common for mass manufacturing, but less so for the low volume production scenarios often associated with AM. In contrast, further empowering existing AM processes towards a capability of realizing integrated “smartness” in few or even a single AM process seems a promising approach which deserves extended interest from the research community. From an analysis of their main characteristics, many processes can be identified that may in future develop towards this ambitious aim. Prominent among them are those which, even today and for different material classes, offer first approaches towards a controlled spatial distribution of different materials within the building volume. Typically, these are not the processes that work with a bulk of either liquid or particulate materials which is locally consolidated (vat photo polymerization or powder bed fusion processes), but rather those that feed material as they build the part, like material extrusion, material jetting or directed energy deposition, as well as, to a limited degree, binder jetting.

Assuming that the related challenges can be successfully addressed, we see a bright future for AM specifically in its relation to material-integrated sensing, for the simple reason that the combination of these technologies will pave the way for a broad introduction of advanced, IoT-capable products that contribute the customization and part complexity aspects so typical of AM parts to the smart product field.

Despite this advocating of single-process approaches, it is important to note that their advent is unlikely to eliminate the relevance of other, hybrid or separate process approaches. Despite their many advantages, complete reliance on single process techniques will always impose limits upon the scope and combinations of materials which can be used in a single part. Such limitations may affect performance and may thus not be acceptable in some applications. One example that illustrates such concerns is the copper wire embedding process studied by Wicker et al. and Shemelya et al. [67,87], which is motivated by the fact that printed or dispensed conductive paths fall short of pure metal wires in terms of their achievable conductivities.

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