Engineering

ADDITIVE MANUFACTURING AUTOMATION FOR INDUSTRY 4.0

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ABSTRACT:
DIGITAL TOOLS SUCH AS CAD/CAE OR SIMULATION, DIGITAL DIRECT MANUFACTURING TECHNOLOGIES SUCH AS ADDITIVE MANUFACTURING, ROBOTICS AND AUTOMATION, VIRTUAL AND AUGMENTED REALITY ARE NOW SHAPING THE ENGINEERING WORLD. THE CONNECTIVITY PHYSICAL-DIGITAL AND DIGITAL-PHYSICAL INCREASED DUE TO A SIGNIFICANT INCREASE IN THE MACHINES' CAPABILITY TO COLLECT AND INTEGRATE DIFFERENT TYPES OF DATA AND TO INTELLIGENTLY AND AUTOMATICALLY REACT UPON DATA ANALYSIS RESULTS. THEREORE, IT BECAME POSSIBLE EXPLOITING THESE TECHNOLOGIES TO THEIR FULL POTENTIAL. THIS IS ESPECIALLY TRUE FOR ADDITIVE MANUFACTURING SYSTEMS THAT FOR YEARS FUNCTIONED IN A STAND-ALONE MODE AND WHICH NOW HAVE STARTED TO BE AUTOMATIZED. BY AUTOMATION, ADDITIVE MANUFACTURING CAN BETTER FIT INDUSTRY 4.0 PARADIGM AND IT CAN BE USED FOR COUPLING MORE EFFICIENTLY THE DIGITAL WORLD WITH THE TANGIBLE MANUFACTURING.
THE PAPER IS FOCUSED ON ANALYZING THE STATE OF THE ART IN AUTOMATING ADDITIVE MANUFACTURING PROCESSES IN ORDER TO ASSESS THE CURRENT CHALLENGES AND LIMITATIONS, AND ALSO TO OFFER A PERSPECTIVE OVER OPPORTUNITIES AND APPLICATIONS.

KEY WORDS: ADDITIVE MANUFACTURING, AUTOMATION, INDUSTRY 4.0, DATA INTEGRATION

INTRODUCTION

Looking at engineering history one can observe how concepts, technologies and processes have evolved, connected and sustained each other for achieving more and more complex levels. This retrospective view can be useful for understanding future developments and for positioning ourselves so that to be prepared not only to efficiently react to change, but also to actively participate in to it. Nowadays the industrial world came to a point when different existing manufacturing technologies, digital tools, devices, processes and systems can be connected by networks (Internet of Things – IoT) and can reciprocally exchange information so "that the product communicates with the machinery to tell it exactly what to do"[3]. It is the 4th industrial revolution (Industry 4.0 – as defined in 2011 at Hannover Messe,

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[3] Sniderman, B., Mahto, M., Cotteleer, M.J., Industry 4.0 and manufacturing ecosystems available at https://dupress.deloitte.com/content/dam/dup-us-en/articles/manufacturing-ecosystems-exploring-world-

Germany). This means a change in the way the conventional production processes work and it is based on establishing the connectivity physical-to-digital and digital-to-physical, i.e. between the tangible manufacturing and the digital world (Cyber-Physical Systems – CPS). Moreover, there is a permanent and seamless share of information within and between these 'worlds', so that machines' actions in the production process are determined by data analyses, by mapping the physical world to the digital world (digital twinning).

Digital engineering tools (CAD/CAE and virtual simulations, for instance), additive manufacturing (AM) technologies, virtual and augmented reality, embedded sensors and systems, internet technology, robotics and automation, etc. are used for years in many applications and production processes. In other words, these technologies and tools are not new: SketchPad - the first Computer aided Design (CAD) system was developed by Ivan Sutherland in the 60's[4], Virtual Reality concept and first applications were created in 1989 by Jaron Lanier[5], augmented reality was initially used in 1992 by Caudell and Mizell in an application for Boeing[6], AM Stereolithography process was patented 30 years ago[7], etc. What is new is the development of capabilities to collect, intelligently monitor and interpret data from different sources and synchronize them across different functional systems. Thus, even if the aforementioned technologies, tools and systems are mature and already proved their advantages in products' design and manufacturing processes, they can get a new value within Industry 4.0 (IR 4.0) frame. This is the case of AM technology and AM machines – for years functioning in a stand-alone mode, which now due to technology and material advances can and should be automatized. In the current view over IR 4.0, 3D printing is viewed as one of the pillars (fig.1). However we consider that in order to fulfill this role, AM automation is required. By automation AM can be deployed at a production-scale and, thus, it can better find its place in IR 4.0 paradigm as shows the late developments of the main AM producers[8].

connected-enterprises/DUP_2898_Industry4.0ManufacturingEcosystems.pdf (accessed on February 2017); Germany Trade & Invest, "Smart manufacturing for the future," http://www.gtai.de/GTAI/Content/EN/Invest/_SharedDocs/Downloads/GTAI/Brochures/Industries/industrie4.0-smart-manufacturing-for-the-future-en.pdf , National Academy of Science and Engineering, "Securing the future of German manufacturing industry: Recommendations for implementing the strategic initiative Industry 4.0"

[4] Sutherland, I.E., Sketch pad a man-machine graphical communication system, Proceeding, AC '64 Proceedings of the SHARE design automation workshop, pp.6.329-6.346

[5] Lanier, J., Using Virtual Reality As A Tool To Study The Relationship Between Human Beings And Physical Reality, In Human Machine Interfaces For Teleoperators And Virtual Environments, Nasa Conference Publication 10071, 1990

[6] Claudell, T., Mizell, D.W, Augmented reality: An application of heads-up display technology to manual manufacturing processes, Proc. IEEE Hawaii Intl.Conf. on Sys.Sciences, 992, 659-669 (1992)

[7] Hull, C., Apparatus for production of three-dimensional objects by stereolithography US 4575330 A Patent, granted March 1986

[8] Buelsamid, S., Ford starts pilot testing Stratasys infinite build 3D printer, 6 March 2017, available at https://www.forbes.com/sites/samabuelsamid/2017/03/06/ford-starts-pilot-testing-stratasys-infinite-build-3d-printer/#3ef270a83710 (accessed April 2017); Krassenstein, B., Viridis3D & Palmer Manufacturing Partner to Create a Robotic 3D Printing System, 7 Nov 2014, available at https://3dprint.com/23612/vridis3d-robotic-3d-printer/ (accessed February 2017); 3D Systems Unveils Industry's First Scalable, Fully-Integrated Additive Manufacturing Platform available at https://www.3dsystems.com/press-releases/3d-systems-unveils-industry-s-first-scalable-fully-integrated-additive-manufacturing (accessed February 2017); https://www.eos.info/eos-exhibits-the-future-of-additive-manufacturing-at-formnext-2016-8936f51c2af4b41a; Krassenstein, B., MatterFab Reveals Their Affordable Metal 3D Printer, An Order of Magnitude Cheaper, 2014, available at https://3dprint.com/9592/matterfab-reveals-their-affordable-metal-3d-printer-an-order-of-magnitude-cheaper/ (accessed February 2017); The Additive Manufacturing Factory of Tomorrow, available at http://www.fabricatingandmetalworking.com/2016/05/additive-manufacturing-factory-tomorrow/ (accessed April 2017); Park, R., a good fit: robotics and additive manufacturing, December 2015, available at http://www.disruptivemagazine.com/features/good-fit-robotics-and-additive-manufacturing (accessed February 2017)

Therefore, in IR 4.0 it is not about 3D printing (the name associated to low-cost machines, mostly based on FDM –Fused Deposition modeling process), but about AM.

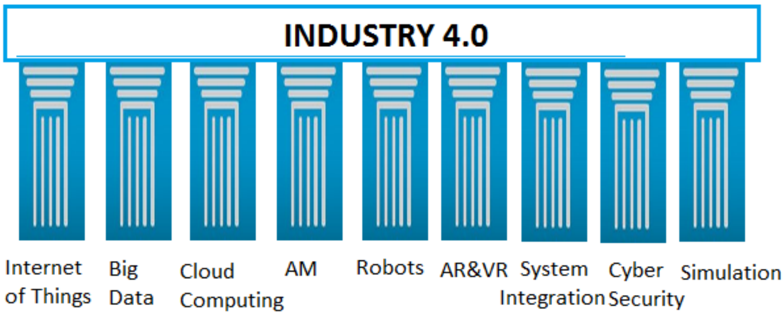

Fig.1. AM in Industry 4.0

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By its definition – "the process of joining materials to make parts from 3D model data, usually layer upon layer, as opposed to subtractive manufacturing and formative manufacturing methodologies"[9], AM establishes a straightforward connection between digital and physical (see figure 2).

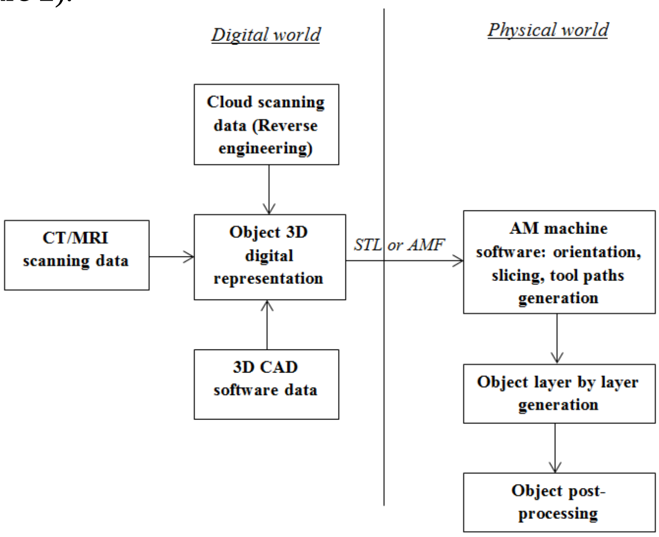

Fig.2. AM technology – a link between digital and physical

AM starts from the digital 3D representation of the object to manufacture, saved in STL or AMF file formats, the following working steps being then applied:

- Import the STL file of the object in AM machine software;
- Orient, scale and/or move the object within the build space;
- Slice the object by parallel planes, perpendicular on the build direction;
- Generate paths for laser, deposition nozzle, inkjet nozzle, etc.
- Manufacture the object by superposing thin layers of material;
- Remove the printed object from the AM machine;
- Post-process the object.

Some of these steps involve manual labor. In fact, most of today's AM machines heavily rely on operators for choosing the orientation, removing the printed object from the machine, refilling the feedstock, performing post-processing operations or fixing different

[9] ISO/ASTM 52900:2015 - Additive manufacturing -- General principles -- Terminology

problems. Therefore, in order to cope with IR 4.0 requirements, AM machines should be able to work independent of operator and to communicate with other AM machines, robots, etc.

Automating the selection of the optimal build orientation based on different criteria (for instance, minimization of support structures volume) is in the researchers' attention for a long time. Different algorithms and solutions were proposed[10]. There are also software applications (Meshmixer, for example) or plug-ins offering suggestions regarding AM parts' orientation. Other options regarding layer optimized or automatic infill based on part's geometry and functionality or automatic temperature setting as function of material also started to be included in AM software for supporting designers' work. But the final decision still belongs to designer/operator. However, based on the advances in artificial intelligence (AI) decision systems, we consider that the problem of preparing the object for AM without human intervention will be tackled soon. And, in the same context, soon enough self-learning AI-based applications will heavily support designers' decisions in applying Design for Additive Manufacturing rules when designing new products.

As mentioned, AM producers have started lately to focus on combining AM, robotics and/or automated handling systems for providing a degree of automation to this technology. In this sense, three main directions are currently targeted:

- Use robots to deposit the layers of material (Robotic Additive Manufacturing). Examples:
    - Robotic Composite and Infinite-Build 3D Demonstrators from Stratasys[11]. In case of Robotic Composite 3D Demonstrator, a multi-axis robot deposition head is associated with a perirobotic system for building the part. The systems also include a tool changing device which allows performing also secondary operations such as drilling, milling, painting, etc. so that the final product is obtained within the same system. Infinite-Build 3D Demonstrator builds the part horizontally using a gantry robot, while pellets are used as feedstock for producing filaments. Different tools and materials can be used increasing these systems flexibility.
    - Viridis 3D printer includes an ABB robot which has as end-effector a print head for binder jetting process from EnvisionTEC[12]. As for Infinite-Build 3D Demonstrator, this platform is also suitable for 3D printing large objects.

In these applications, objects' removal from the building zone at the end of the manufacturing process is performed by human operators.

- Use robots to perform different operations such as loading and unloading AM machines, delivering material, applying post-processing curing operation, etc. Example:
    - Figure 3 from 3D Systems[13] – a fully automatized AM system. The manufacturing speed provided by DLP (Digital Light Processing) process allows obtaining a large number of parts which justifies robots' presence within SLA Bot-1 and SLA Bot-2 systems. This is an example of successful

[10] S. Allen, D. Dutta, Determination and evaluation of support structures in layered manufacturing, Journal of Design and Manufacturing, 5 (3) (1995), pp. 153-162; Paul, R., Anand, S., 2011. Optimal Part Orientation in Rapid Manufacturing Process for Achieving Geometric Tolerances. 30(4), pp. 214-222; P., Wits, W.W., Design for Additive Manufacturing: Automated build orientation selection and optimization, Procedia CIRP, Volume 55, 2016, pp.128-133

[11] Buelsamid, S., Ford starts pilot testing Stratasys infinite build 3D printer, 6 March 2017, available at https://www.forbes.com/sites/samabuelsamid/2017/03/06/ford-starts-pilot-testing-stratasys-infinite-build-3d-printer/#3ef270a83710 (accessed April 2017)

[12] Krassenstein, B., Viridis3D & Palmer Manufacturing Partner to Create a Robotic 3D Printing System, 7 Nov 2014, available at https://3dprint.com/23612/vridis3d-robotic-3d-printer/ (accessed February 2017)

[13] 3D Systems Unveils Industry's First Scalable, Fully-Integrated Additive Manufacturing Platform available at https://www.3dsystems.com/press-releases/3d-systems-unveils-industry-s-first-scalable-fully-integrated-additive-manufacturing (accessed February 2017)

integration of an AM machine into a fully automated manufacturing environment.

- Use automated handling systems for transferring objects within different modules of an AM system. Examples:
  - o EOS M400-4 modular platform[14], which includes four lasers for layer formation for increasing the productivity, as well as automated transfer of objects between stations, automated material feeding and automated part cleaning.
  - o Additive Industries MetalFAB1 is also a modular platform which includes automated handling systems that transfer objects from a module to another for performing operations such as post-processing, cleaning, heat treatment, object measurement etc. Airbus already purchased such automated metal-based AM systems which offers productivity and quality[15].

Software producers such as Siemens PLM (Simcenter portfolio), PTC (Creo 3.0 Additive Manufacturing M040 module, fig.4), Dassault Systemes (Simulia for Additive Manufacturing) are now offering the so called "end-to-end additive manufacturing software package" containing tools that cover the entire AM product cycle: design, optimization and production. Partnerships between software producers and manufacturing systems producers were established, such as Siemens PLM and DMG Mori for the hybrid manufacturing module in NX (fig.4), Siemens PLM and Stratasys (for Robotic Composite and Infinite-Build 3D Demonstrators) or Siemens and Trumpf (for developing TruTops Print with NX software solution).

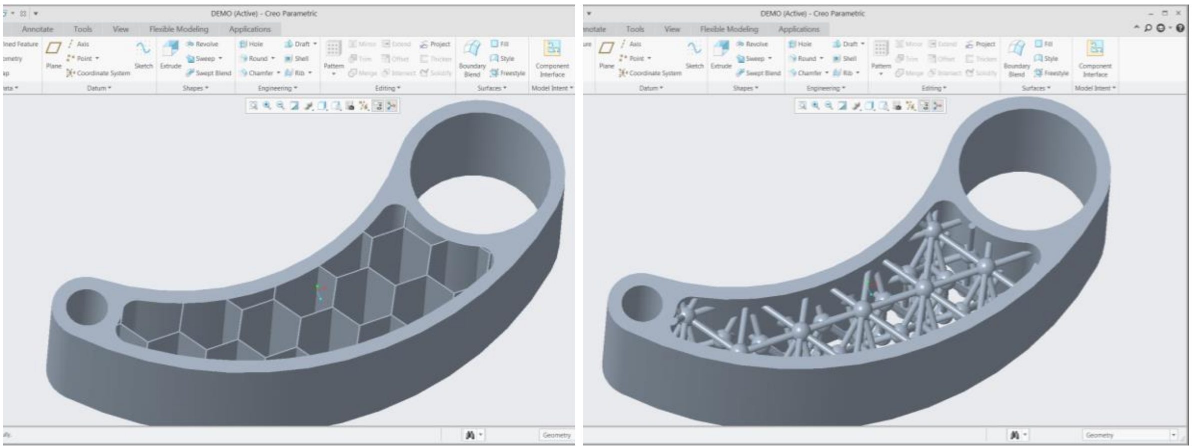

Fig.3. Creo Additive Manufacturing – example of generated lattice structures

[14] https://www.eos.info/eos-exhibits-the-future-of-additive-manufacturing-at-formnext-2016-8936f51c2af4b41a

[15] Krassenstein, B., MatterFab Reveals Their Affordable Metal 3D Printer, An Order of Magnitude Cheaper, 2014, available at https://3dprint.com/9592/matterfab-reveals-their-affordable-metal-3d-printer-an-order-of-magnitude-cheaper/ (accessed February 2017)

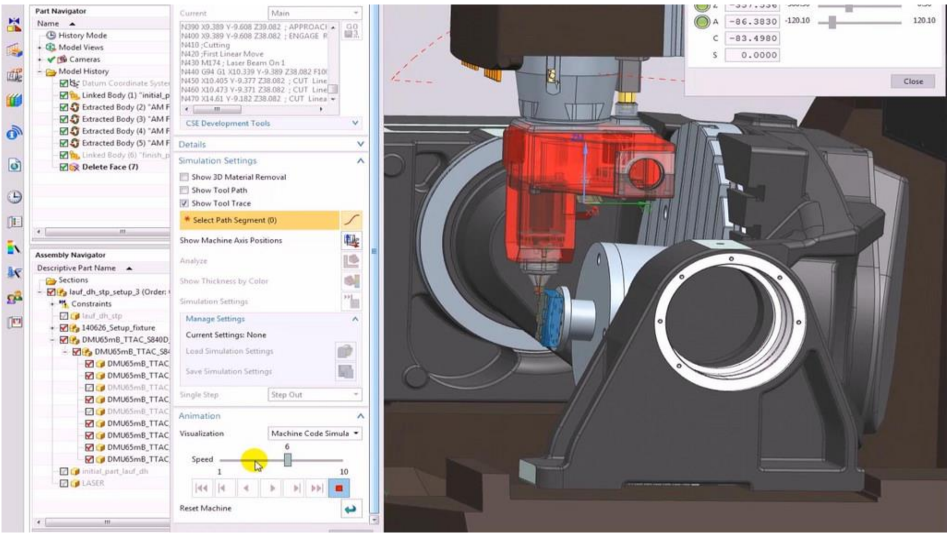

Fig.4. Screenshot NX CAM Hybrid Additive Manufacturing

DISCUSSION AND CONCLUSIONS

Despite indisputable advantages, the way AM technology was implemented until now (i.e. standalone machines, manual labor for part build orientation and post-processing operations, etc.) makes difficult its integration within the production flow of IR 4.0. In this context, producers are working for changing AM paradigm and their business focus. Therefore, all the intelligent AM solutions presented in our survey are conceived to be included in smart factories, showing how producers decided to comply with these new concepts. In the same time, they are the expression of producers' vision over the development of the AM field: automation, focus on metal-based AM processes, focus on product customization, enlarging the build space (Big Area AM trend), development of end-to-end (from product design to product manufacturing based on AM) solutions.

AM automation involves automating the steps of the working flow which are currently executed by human operators, parameter settings optimization, automating AM machines' loading and unloading, post-processing and also using robots for depositing layers. Moreover, one can also notice that by developing automated AM systems producers are in the same time trying to increase the productivity of their machines/process. It is the case of 3D Systems which automatized a process (DLP) 50 times faster than SL process or the modifications made by EOS to M400 machine so that to include four lasers for manufacturing a larger number of parts.

CAD, CAM, CAE software producers are following the same trend for their developments by proposing integrative solutions for the design process of AM products, optimal process parameter settings and AM process simulation.

AM in IR 4.0 environment has nothing in common with the "3D printing democratization" trend started in 2009. In preparation for IR 4.0 many challenges are still ahead. One of them is related to the production flexibility (customization and individualization being highly required by today's clients) at low costs. Here AM can bring its advantages if automated. However, considering the investments in research & development activities necessary for implementing such automated solutions, we consider that only big AM producers together with big CAD, CAM, CAE software producers can accomplish the discussed goals.

ACKNOWLEDGEMENTS
This work was supported by a grant of the Romanian National Authority for Scientific Research and Innovation, CNCS/CCCDI – UEFISCDI, project number PN-III-P2-2.1-BG-2016-0036, within PNCDI III.

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