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A Digital Twin architecture for monitoring and optimization of Fused Deposition Modeling processes

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Abstract

In the realm of the fourth Industrial Revolution, digital technologies are constantly integrated in Manufacturing processes in order to improve system reliability, monitor processes accurately and ultimately optimize processes. In order to tackle these issues, advanced simulation techniques such as Digital Twins (DT) have to be developed. Further to that, modern manufacturing systems are based on the integration of non-conventional processes, such as Additive Manufacturing (AM). Therefore, in this research work a Fused Deposition Modeling (FDM) DT is designed and developed, integrating quality assessment modules. Furthermore, a database has been modelled in an attempt to monitor all the experiment results. Additional modules have also been created and integrated, such as compensating the effects of printing, as well as immersive interfaces enabling the users to control and monitor the machine state remotely. Consequently, one of the key concepts of this paper is the design of the information flow between the above-mentioned modules for optimizing the FDM process parameters, and thus minimize time and resources caused by human error. The implementation of the proposed framework is based on the integration of suitable communication channels.

Keywords: Fused Deposition Modeling; Additive Manufacturing; Digital Twin; Mixed Reality

1. Introduction

According to the official definition, Additive Manufacturing (AM) refers to all the non-conventional manufacturing methodologies, i.e. subtractive and formative manufacturing, based on the disposition of material on layer-by-layer fashion [1]. Under the Industry 4.0 framework, AM has been thoroughly investigated and several new technologies and techniques have been developed and integrated [2]. Further to that, recent reports state that the market growth of AM, including 3D printers, materials, and services has reached 3 billion USD in 2020 [3].

On the other hand, due to the constant developments in information and communication technologies (ICT), advanced simulation techniques, such as Digital Twins are being utilized in order to monitor manufacturing equipment, predict future states, and most importantly optimize manufacturing processes based on real data derived from the shop-floor level [4]. The integration of Digital Twin technology in manufacturing is constantly growing, as a result of the digitalization companies are undergoing, and it is estimated that the Digital Twin market will reach 35.8 billion USD by the end of 2025 [5].

Due to the nature of the AM processes, defects in the manufactured parts have to be spotted early in the production phase, in order to avoid producing defecting parts. Common issues arise in surface quality, warp of the geometry due to the heat, incoherence of layers. Taking into consideration that AM processes have lower production rates, it becomes necessary to constantly monitor the AM processes and by extension to make the necessary adjustments in order to reduce the number of defective parts, thus increase the overall quality of the AM process. Therefore, in this research work the design and development of a digital twin architecture for Fused Deposition Modeling (FDM) processes is presented. The digital twin will

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be utilized to provide monitoring and control capabilities remotely, as well as compensate defects. Furthermore, the implementation of an immersive Augmented Reality (AR) interface for the digital twin is also proposed. By extension, the main contribution of this research work is focused on the reduction of production costs of AM products, either from detecting a complete failed process and stop it, or by preventing defective and low-quality 3D prints through the simulation results and the inspection of previous prints. Further to that, the proposed framework provides an advanced method of controlling and utilizing the FDM 3D printer, that could assist product designers, and people without deep knowledge on the process to achieve better results.

The rest of the paper is structured as follows. In Section 2 the most pertinent and relevant publications are investigated. Then, in Section 3, the architecture of the proposed framework is presented and discussed. Then, in Section 4 the implementation steps are presented. Consequently, in Section 5 the results are presented. In Section 6, conclusions are drawn, and future research directions are provided by the authors.

2. State of the Art

AM is a tool that offers increased “design freedom” and enables designers and engineers to create unique products that can be manufactured in low volumes. FDM is a well-known AM technology, which although is capable of manufacturing adequate results there is fertile ground for further improvement [6]. Consequently, the authors in [7] have presented and algorithm for controlling the speed of the 3D printing head, as it is directly correlated to the quality/smoothness of the manufactured product. Similarly, in the research work presented in [8] the parameter of part cooling is taken into consideration in order to sufficiently compensate shrinkage, by adjusting appropriately the internal geometry of the part. In the extensive literature review of Mohamed et al. in 2015 [9] a complete list of the FDM process parameters is provided, proved to be useful for the quality optimization of the manufactured products. More specifically, the key process variables include liquefier temperature, build environment temperature and filament feed rate. Thermal stresses within a part as a melt solidifies and cools to the build environment temperature can lead to warping and distortions of a part. The filament feed rate is used to control the rate at which material is deposited [10-13]. Resolution is a function of the system design, depending on the accuracy of the motors controlling the motion of the printing head in the gantry, the quality of the control algorithm and the print nozzle diameter. The printing accuracy of the curved surfaces in the build plane, which are translated from the CAD design to the built structure, is limited by the minimum step size of the stepper motors controlling x-y motion in the build plane.

Unfortunately, newer industrial systems provide limited if any ability to control these parameters, although studies with legacy systems have provided some important insights into their influence. Therefore, under the vast digitalization of manufacturing companies, via Internet of Things (IoT), Digital Twins (DT) etc., it becomes necessary to develop new simulation frameworks for the monitoring, controlling, and optimizing manufacturing processes [14]. In the available literature, there several frameworks for the prediction of several parameters, such as cycle time, based on the utilization of DT [15,16].Concretely, in the frameworks presented in [17-27], various simulation techniques are utilized, for the acquisition of data from the processes, aiming at the prediction of optimal process parameters and optimization of product quality. More specifically, in [18] the authors have developed a DT-based framework for monitoring the performance of FDM processes based on the utilization of real-time process data and the detection of anomalies. What is interesting is that the authors have introduced a key performance indicator for monitoring the energy consumption of the machine. Mandolla et al. in [19] have presented an interesting approach for the integration of DT in AM, based on the utilization of Blockchain technology. By extension, the authors have focused on securing and organizing efficiently the data generated and exchanged between the physical part and the digital part of the DT. In [20], Liu et al. have developed a collaborative framework, which enables the communication of several DTs, implemented as Edge devices, with a “master” DT installed on the Cloud aiming at improving the quality of AM parts. Klingaa et al. in [21] have investigated the creation of suitable data models towards the implementation of DT in AM, and specifically in laser powder bed fusion. Cai et al. in [22] have proposed a framework for the synchronization of multiple robotic arms acting as extruders for 3D printing, based on the utilization of DT technology. Furthermore, in this approach, AR is also integrated in order to visualize the virtual counterpart and make adjustment to the system. In [23] Scime et al. have developed a scalable DT-based platform for minimizing the need for physical tests, by integrating predictive Artificial Intelligence algorithms. Henson et al. in [24] have developed an interesting DT framework for the monitoring of AM processes by applying a multi-sensor optical system for inspecting part distortion in a layer-by-layer fashion.

Taking into consideration the above-mentioned, the contribution of this paper can be summarized to the design and development of a DT framework based on the utilization of common process data for the provision of suggestions to the engineers as well as for performing online and offline simulations. Ultimately, the main research question to be answered is if the integration of DT and AR in FDM could facilitate in improving the quality of 3D parts, as well as to minimize human errors caused by incorrect machine setup.

3. Proposed FDM Digital Twin architecture

A typical example of a conventional FDM process is considered as a base line, in order to present the key points where there is room for improvement for the process. Concretely, the first step of the FDM process is the extraction of the 3D model from the CAD. The next step is the verification of the part dimensions in comparison with the specifications of the printer (i.e., maximum printing dimensions). In case that the size of the part exceeds the maximum printing range of the 3D printer, then the engineer revises the CAD file. Then, in order to achieve the effect of rapid prototyping, before 3D printing, the 3D CAD of the object is sliced into a layer-by-layer section. Afterwards, the slicing algorithm creates a dataset corresponding to the slices of the object, including information about the shape, the size etc.. Then the G-code instructions are created and transmitted to the 3D printer in order to start the manufacturing process. The system architecture of the proposed DT is presented in Fig. 1, in which the physical and the virtual environments have been highlighted along with the information flow. Furthermore, in Fig. 2 a more detailed visualization of simulation processes is presented.

After the initialization of the process the machine starts executing the provided G code. At this point of time, the machine operator cannot interfere with the process, they can however, monitor the process in order to identify potential flaws that may lead into a defective part. In this case the optimal action is to stop the process in order to minimize material and operational time loss. The process parameters must be reevaluated, the slicer settings to be adjusted before restarting the process.

The Human Machine Interaction of the machine operator with the 3D printer is clearly outdated. Also, the monitoring aspect of the process could also be improved and automated. Finally, as most of the process settings are been defined through the slicer before the process takes place, it would be very beneficial for the operator or the designer to have some prior knowledge on the machine state and how the different setting could affect the final part.

In an attempt to address the above-mentioned literature gaps, a Digital Twin architecture and workflow is presented that potentially could improve the quality of the printed part, as well as reduce the cost in the long run. Initially, the 3D printer is established as a Cyber Physical System (CPS), capable of publishing information to a network, and receiving input such as G code and basic commands from other devices connected to this network. The proposed DT will be developed as an attachment to the conventional setup of an FDM 3D printer. The ability to initialize a process remotely is essential since some commercial 3D printers support it out of the box. By including a Cloud database in the workflow, the FDM process information are stored for later access for the Digital Twin (DT) to be able to provide insights prior to a process execution about the setting and the quality of the fabricated parts from 3D printer, the proposed Digital Twin will utilize an AR interface where the process would be replicated, by superimposing the 3D printer in the real environment with AR technology.

A Graphical User Interface (GUI) is needed to display all the information coming from the 3D printer, as well as host various control functionalities. Initially the GUI grants access to the 3D printer controller, for monitoring critical parameters and adjusting their values on-demand. As regards, the offline simulation, users can preview a simulation of the 3D printer performing past prints, including images from the process and the manufactured part, through a camera, which is installed on the 3D printer. Finally, the users are able to inspect the stored results and adjust the slicer settings based on the previous successful printing setups. On the other hand with the online simulation, the virtual preview of provided G code is enabled. Furthermore, the G code generated by the users can be executed through the DT interface and the users can monitor the process remotely.

The scope of the FDM DT framework is to be adjustable in order to fit the customer needs or the target market sector. The general idea is to enhance the capabilities of a current FDM printer, also making the technology more accessible to designers, engineers or hobbyists that may not fully exploit the capabilities of an FDM printer.

The concept of an intuitive user-friendly interface with only the required settings available to the user, could target the market of hobbyists, by providing it as an application or service. Furthermore, FDM 3D printer manufacturers could be interested in such an interface to be integrated to their machines since low-cost 3D printers are paired with the basic software with little to no tuning capabilities. Also, it can be found in the market 3D printers are shipped with wireless functionalities. This kind of intuitive interface paired with the above-mentioned functionalities focuses more on the remote-control aspects as well as the prior knowledge of the FDM process that can be provided from the framework.

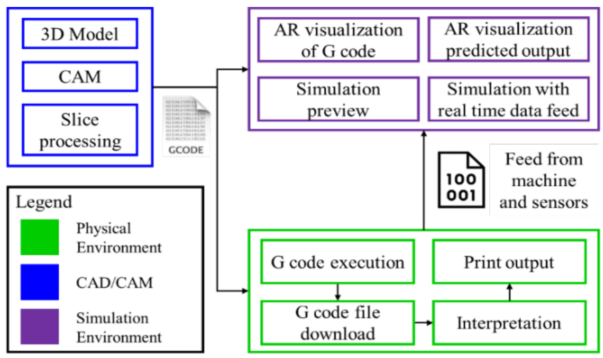

Fig. 1. Proposed 3D-print data-processing with Digital Twin implementation

In order to achieve this level of automation/servitization, the following technologies and techniques must be combined and integrated to the existing solutions. The FDM 3D printer firmware allows for the operation and control of the machine. IoT capabilities of the machine, along with integrated hardware enable the connection of the FDM 3D printer to the factory network. Integration of external hardware to monitor the machine. A suitable communication pipeline is necessary, by means of a communication protocol, or a combination of protocols for achieving the information exchange between the components of the DT framework. A loud database is also required, so that data can be stored, analyzed, and accessed later. GUIs, so that the immersive interface and machine visualization to be achieved.

Initially the user can perform a review of past build results and adjust the machine settings. Following, the G code generation from the slicer takes place. The DT displays a preview to the user of the imported G code, the Offline simulation is a close feedback loop where the user can adjust the machine settings and compare results continuous until the simulation results are satisfactory. The DT methodology presented aims at providing to the user knowledge on past setup slicer profiles and 3D printer configuration. Thus, the DT provides high adjustability on the process, the parameter are classified into slicer related and 3D printer related parameters.

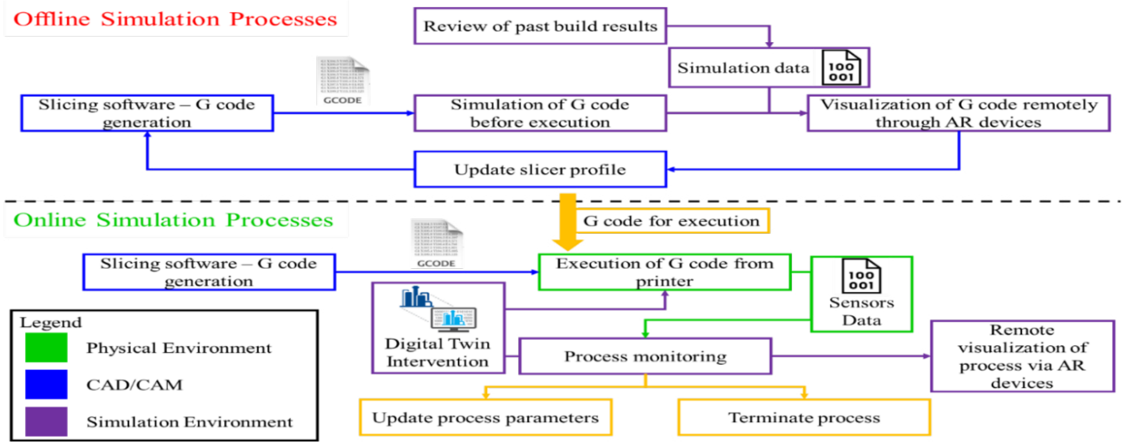

Fig. 2. FMD Digital Twin framework information flow

In order to perform an initial calibration of the slicer profile, as well as provide a first input of reference prints to the digital twin a set of calibration models was sent for printing. The initial test model was a benchmark boat, the model is a small boat of 20mm length and 8mm width. From this first test print under extrusion was detected thus the steps of the extruder motor were recalibrated. Another test print that was performed was focused the retraction distance and speed of the extruder, the model for this test was 2 parallel cylindrical towers of 5mm diameter each. The G code for this test was customized to change/increase, the retraction distance every 5 layers. The results were that stringing effect was reduced in the upper layers of the print, and thus an appropriate value for retraction distance could be selected. Similar tests prints were also performed for retraction speed, base speed, and acceleration tuning. After concluding to a set of slicer settings the final G code is generated. Then the user selects the relevant printer configuration settings, based on past prints. The G code is sent for execution from the physical printer. Simultaneously, the online simulation from the DT is initialized.

4. System Implementation

For the DT to gain more control over the 3D printer as well as enhance its capabilities the installed firmware was replaced by the Klipper firmware, which partially runs at an external microcomputer, e.g. Raspberry Pi. This configuration offers a lot of advantages as typically the mainboard of the 3D printer that hosts the firmware is an 8-bit board. With the Klipper configuration the processing power of the Raspberry Pi is combined with the capability of the mainboard build in motor drivers to control the printer motors. Consequently, all the resource intensive calculations are executed by the Raspberry Pi processor, and after processing the G code, the commands are sent to the main board of the 3D printer. The G code commands are sent to the motor drivers, line by line in real time. In order to monitor this process, a custom terminal on the Raspberry Pi is setup. Furthermore, the Klipper firmware can serve the purposes of the proposed DT as the 3D printer configuration values are stored in an XML file, on the Cloud database. By extension, the configuration file can be altered at any time, offering extended flexibility and adaptability of the DT, and the proposed framework as well. However, if the user makes any changes to the configuration file, they are applied only after the system is reboot. The functional specifications include details regarding how the application will interface with, for example, legacy applications, provide database models and describe the relationships between the different data entities, and detail how each component of the application interacts with every other component.

AM requires a preparation process for the generation of the G code that will be executed from the FDM 3D printer, along with the export of a potential CAD design to Stereolithography (STL) format process. The preparation processes are defined in the architecture of the FDM DT as a module not fully integrated to the software system. Even this is one of the most important parts of the process it will not be integrated as a software that directly communicate with the other modules. The preparation of the process is one of the most important parts, as most of the parameters that will affect the properties of the resulted part are defined during this step. The framework will aim on providing knowledge to the user regarding his initial settings through an immersive simulation. Through this simulation the user will be able to have a first impression on how the G code he provided will result as a part after the process. Thus, the framework will provide to the user guidance on how to altern the setting on the slicer and the machine. The user can make use of his preferred CAD or design software and also Slicer, in the presented implementation the Ultimaker CURA slicer will be used.

The pre-processing module containing the Slicer interacts with the rest of the modules of the DT through the Cloud database. The resulted G code file along with the original STL model will be uploaded after generation of the G code so that it can be retrieved from the other modules. The Slicer profile used is also uploaded and stored along with the relevant G code file. By analyzing the slicer profile the G code and the resulting part the user can have a better estimation on how the manipulation of the Slicer settings will affect the 3D printed part and the process overall.

The Cloud database of the system will act as an online shared memory between the modules of the proposed framework. All the information from the DT are stored in the Cloud database, except from the STL models, the G code files, and the setting profiles. The log files, which are stored on the Cloud database, are used to track the status of the machine, and remind the user for services that may need to occur after a number of operational time. Also, in the future for the enhancement of the framework with the implementation AI algorithms, and this info could be used for potential training of a neural network. The files that will be actively used and continuous accessed from the framework modules will be grouped together per process. After the completion of a print, all the relevant files will be stored in the database based on the model presented at the Fig. 3.

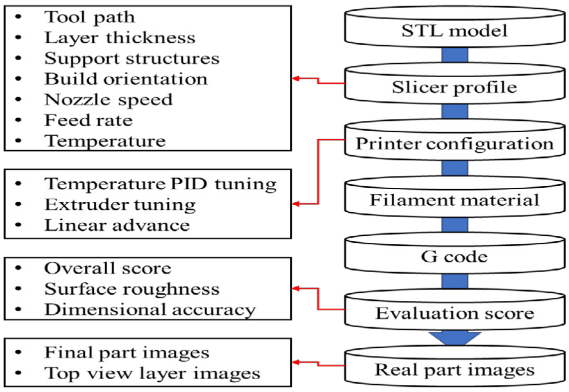

Fig. 3. Description of a process on the database, based on the data exchange between the different modules and the parameters imported by the user.

The microcontroller hosts all the software required for the online monitoring of the machine. In order to do this, a serial bus connection is set up with the controller of the machine. Afterwards, the microcontroller retrieves all the information from the FDM 3D printer regarding its state, the current process, and the motor values as well. The information from the machine is published to a web-dashboard that is hosted to the microcontroller. Thus, all the printer control and monitoring sub-modules can be accessed through this microcontroller. Furthermore, with the integration of a camera to the microcontroller, visual feedback to the user can be provided. The camera settings are also controlled from the microcontroller.

This module will facilitate the interface that the user will use to interact with the DT framework. Two possible interfaces are proposed one that will be implemented at a mobile device, utilizing the AR core capabilities of modern smartphones. Also the application could be applied to AR headsets also with minor modifications in the software.

5. Results and Discussion

The validity of the proposed framework has been tested in a laboratory-based machine shop, in which a variety of 3D-printed components are manufactured either for rapid prototyping or for direct installation in an assembly. It is therefore necessary that the quality of the quality of the manufactured components falls within the tolerances. Before the implementation of the proposed DT, it has been observed that approximately three out of ten 3D printed components required post-processing in order to achieve the desired quality standards.

Further to that, approximately one out of ten components had to be remanufactured as they were severely faulty. However, with the implementation of the proposed DT framework, the engineers could successfully utilize information from previous 3D-printings, as well as adjust the machine more appropriately based on the recommendations the get through the AR GUI and therefore, no faulty parts were manufactured. However, only approximately two out of ten components required post-processing to some extend in order to meet the desired quality standards.

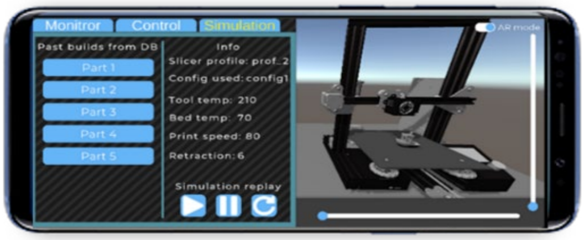

Fig. 4. Augmented Reality GUI on Smart Device

The use of the DT also significantly reduces the required time for fine tuning the parameters in possible change on the processed material or the working temperatures of the machine. Test print results displayed through the DT provide engineers with slicer parameter values that would require printing of test models to fine tune when a change of material is required.

The possibility of altering the configuration file of the machine, allows for immediate change on the PID values of the hot end and the print bed. Thus on a possible change of material that requires different temperature values, time would not be wasted on tuning the PID values of the machine. Neither time loss on test prints to find out slicer settings.

6. Concluding remarks and Outlook

In this research work, the design and development of a framework for monitoring and optimizing the parameters of FDM based on the utilization of DT and Cloud technology has been presented. more specifically, with the proposed framework, which is realized as a mobile application, engineers can run both, offline and online simulations. Based on the development of AR-based immersive GUIs, remote operation and monitoring of the machine has been enabled. Following the completion of each process, the quality of the additively manufactured components is assessed manually by the engineer, and the results are stored in Cloud database for future reference. Finally, the users can review historical quality assessments in order to optimize the process parameters based on historical results and get recommendations for the process parameters as well.

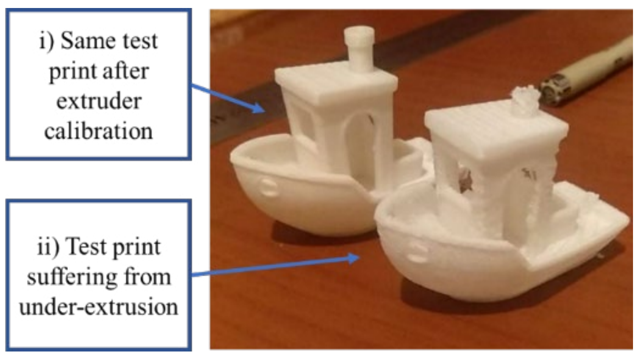

Fig. 5 i) 3D printed part with corrected parameters; ii) 3D printed part with non-optimal parameters

Future research work will be focused on the implementation of a machine vision system to the proposed framework, in an attempt to fully digitalize FDM processes, as well as to get acquire more data about the quality of the additively manufactured components and avoid stringing of the part during the printing process. Further to that, future research will also be focused on the integration of Semantics in the proposed framework in an attempt to adequately structure the information and formalize it, in order to build knowledge from past AM processes, and thus provide better suggestions to the engineers. Furthermore, an additional future research point could be the development and training of an Artificial Neural network based on the dataset built and updated on the Cloud database.

In the current version of the developed application, the interfaces are focused on smartphone platform interfaces with integration of Android AR core SDK. For later stages of development, more advanced algorithms will be implemented to allow realistic simulation of the process in AR environment. The ability to interact with the virtual object in a virtual environment is a method that could be implemented directly on the G code. As a result the designer would have the ability to preview the object on a 1-1 scale and adjust final details from the DT.

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