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On the generation of validated manufacturing process optimization and control schemes

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Abstract

Manufacturing process related functionalities, like optimization and control, are in general demanding in terms of data, computational time and efficiency. However, there are no generic certification or validation schemes that can be followed. In particular, only ISO application can verify the suitability of operations up to an extent. The current work utilizes an enhanced version of Blockchain so that functionalities at the process level can be certified as per a particular scheme. The concept of ledger is elaborated to this end, to manipulate knowledge and be able to handle it like an asset that is exchanged. Thus, a specific generic framework is proposed, herein, to reassure that the right kind of information has been exchanged during process control and optimization. Furthermore, expert distributed agents are utilized to turn knowledge into certified procedures. Encryption issues are also regarded, providing safety and security as extra characteristics. The case study of thermal process control is regarded in this sense to prove the complementary character of these concepts and the usability of the framework. Finally, the existence of additional features within this loop is discussed, like the validation of quantifying concepts like resource streams.

Keywords: Manufacturing Process; Design; Control; Blockchain

1. Introduction

Manufacturing processes in general exchange sensitive data during an operation with various actors. Such actors can be machines themselves, monitoring devices, i.e. vision systems and acoustic emissions, the technician/engineer who operates them, and the engineer who supervises the process even from a remote mode, maintaining the correct planning [1, 2]. It is clearly understood that the transactions between the aforementioned actors should be reliable and un-hackable for potential digital attackers into the industry's network [3].

The emergence of security issues in transactions of data introduces among others the Blockchain technology, considering encryption between peers of transactions and decentralized data. The Blockchain has been reported as one of the nine technological pillars in the context of Industry 4.0 [4]. The business value of Blockchain is expected to explode to $176 billion by 2025 and $3.1 trillion by 2030 as Gartner predicts [5].

Broad research is done on a supply-chain level of manufacturing systems [6], and in particular, in the Additive Manufacturing (AM) domain, several publications concluded that distribution among peers (each one representing a node in the supply chain) could enhance the data exchange keeping the cryptosystem also relative [7, 8]. Deloitte [9] reports that the digitalization of AM may be imposed on cyber risks associated with all the stages taking place in the process. All connected nodes should be considered as vulnerable in order to protect as much as possible the entire property of firm data.

Another report from Deloitte [10] reads that the digital threads are to be considered from the very early design phase

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(CAD creation) to advanced simulation development, definition of process parameters, and initiation of fabrication, even inspection to end-of-life. All the aforementioned stages exchange valuable and sensitive data with each other and security issues are important in these exchanges. Recently, Papakostas et al. [11] proposed a framework (focused mainly on the design phase) to solve the data management system in additive manufacturing. Moreover, a number of authors investigate the security issues in Cyber-Physical Systems (CPS) over the distributed closed-loop process with the main connection to be IoT devices [12, 13]. The increasing number of sensors and actuators with remote-controlled systems also increase the concerns over the trustability of the network, besides the deterioration of performance of a closed-loop system with the delays deriving from itself network or the computational time of IoT [14, 15]. The reduced wiring and flexibility provided by such devices should meet the requirements of the new trusted network [16].

Furthermore, determining the impacts of digital threads on the process chain is important to maintain the properties of firms within the employees and customers, offering limited information access. At the same time, the need for certification increases, advancing the needs for sharing, certifying, and commonly manipulating data and procedures in a standardized way [17]. Typical agencies for certification vary from government to healthcare, finance, and other stakeholders [18, 19]. Other certifying agencies, application-dependent though, are NASA, ASTM, ISO, and others as described by Seifi [20]. A plethora of authors address and recognize the importance of the development of standards in industrial processes, and especially in AM [20–23]. In recent years, critical steps were done for the development of standards on a global scale, such as the ISO/TC 261 [21]. Bae et al. [23], in particular, address the challenge of closed-loop control in AM processes in order to keep the final product within tolerances, linking the problem of control with certification schemas, as others have also performed [15].

In the meantime, the AM processes provide customized products to the customers, therefore reliable transactions between the business-client and between the staff should be established in order to sustain the integrity of data.

This research work deals with the concept of the distributed ledger at the process level in manufacturing, particularly in thermal processes control, such as AM or welding. Hence, a generic certification scheme has been developed for thermal process control involving all data-related agents/users. The communication implicates the existence of an expert agent for the process control who “Certifies” that the operation should proceed with the nominal procedure.

2. Approach

Transactions from the process level are available only for trusted peers. This is the main axiom of the method, while a typical process level includes the process itself, the sensing-monitoring system, the process control, and newer technologies such as Digital Twin for the optimization of the process. Each one is presumed to transmit its I/O signals through the Internet of Things (IoT). The initial flow of data derives from the design phase, with the creation of CAD file, the definition of materials, and partially given boundaries of process parameters. Then, the process control determines the final values with a certified procedure through the synthesis of the controller. The introduction of an expert agent in critical processes within a distributed ledger network increases the trustability and traceability of data among the peers in a cloud-based manufacturing environment. Both aforementioned attributes are considered as the key enablers for such a secured process within the bounds of operation [18, 24]. An expert agent guarantees the certification of nominal operation under the designed criteria. To illustrate the implication of an expert agent, a generic framework is proposed in Figure 1 taking into account an additive manufacturing plant and focusing on the process level.

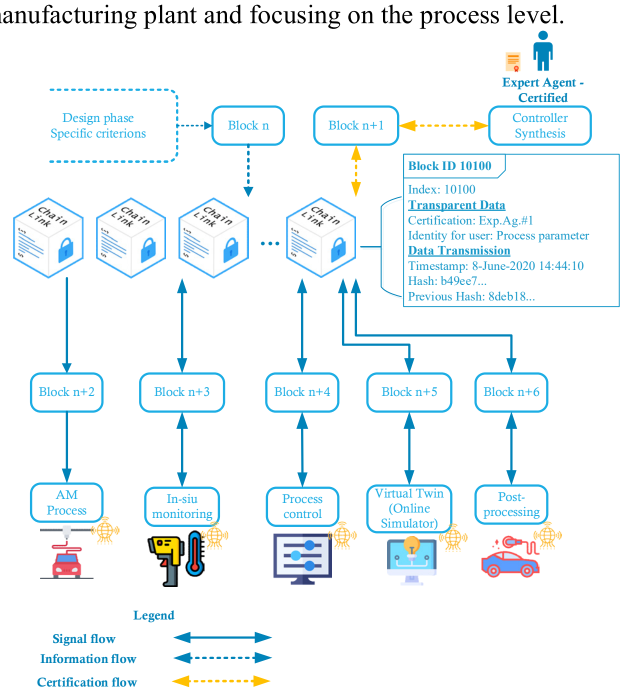

Figure 1 Proposed Framework

Each stage of the particular process transmits with a deterministic hash function a block and this is attached to Blockchain. The established content of each block described in the array of Eq. (1).

$$B = \begin{bmatrix} ID \\ T \\ KPI \\ C \\ H \\ PH \end{bmatrix} \quad (1)$$

- ID_i = block number, *e.g. 10103*
- T_i = timestamp of *e.g. 04-Jun-2020 17:22:42*
- KPI_i = Key Performance Indicator, *e.g. Temperature at melt pool*
- $C_i = [CID_i\ D_i\ K_i]$

CID: Certification Identity, *e.g. control signal, feedback, etc.*
D: Designed by, *e.g. #1 an assigned number to a specific engineer*
K_i: Cryptographic value of CID

- H_i = Hash *e.g. 98cfb324fc951eb5f1ea4cd57b019f349a19f50b2d9cc33eb1174c78fca67806*
- PH_i = previous hash *e.g. 237adaba4d439b2727286d0e63f829e7f4052de60c72fedbd00c1108c9fb0f7a*

All these are used to prove through "broadcasting" in the Blockchain that the operation has been used in a certified schema, i.e. either that the appropriate control signal has been generated or that the correct control has been enforced. There are actually four relevant transactions, as implied by figure 3. The most relevant data that occur in the particular process at the process stage is shown in Table 1.

Table 1: Process related stages and their related data and variables

Process Stage	Related Data
Controller Expert Agent – Def. of process parameters	e.g. power, speed, materials, build plan
In-situ monitoring	e.g. melt-pool geometry, temperature profile
Process control	e.g. regulates predefined variables
Process Post-processing (optional in this application)	e.g. operates with optimal variables
Digital Twin (optional in this application)	e.g. estimates Residual stresses and performs quality assessment

Thus, fundamental certification-related questions can be responded through this framework, as indicated in Fig. 2. The last question, however, annotated in another color, exceeds though the purposes of the current work.

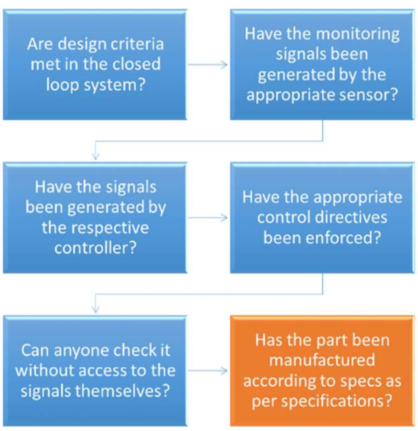

Figure 2 Fundamental certification questions

3. Implementation

A single-input-single-output case study of Laser-based Powder Bed Fusion (L-PBF) was developed to demonstrate the performance of the controller. As input, heat flux was considered, while as output, the maximum temperature occurred in the heating area is taken. For simplicity, no phase change is utilized as the enthalpy inclusion changes significantly the dynamics of the system, exceeding the purposes of this work.

Figure 3 depicts the process control procedure and how the expert agent is implicated in it. As aforementioned, four nodes indicate the transmission of data to/from agent; (i) control signal generation, (ii) control enforcement, (iii) monitoring/sensing, (iv) monitoring/observance.

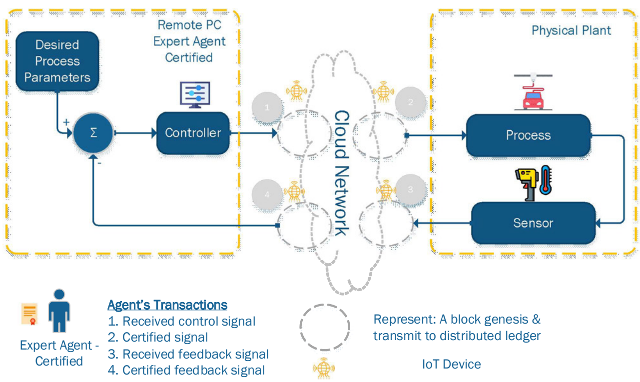

Figure 3 Distributed-ledger Controller

As easily understood from the schematic, numerous delays take place inside a plant. Nonetheless, Table 2 shows only the specific controller's delays that occur with the genesis of block and transmission of the block to the entire Blockchain.

Table 2: Assumption of delays in the process control

Algorithm's steps		Delay
1.	Tracking reference	-
2.	Compute error from feedback	-
3.	Compute control output, build block	$D_{control/block}$
4.	Transmit block through cloud, attach to Blockchain	$D_{control/encr}$
5.	Compute plant's output {Temperature}	-
6.	Sensor signal (transfer function = 1)/build block	$D_{sensor/block}$
7.	Transmit block through cloud, attach to Blockchain	$D_{sensor/encry}$

4. Case study of the validated scheme

In this section, a case study is presented to demonstrate the feasibility and validity of the proposed scheme. A FEM model has been constructed to simulate the AM process. Then, a 3rd order system is used to describe the system, following the identification with the use of parametric identification of ARMAX models. The sampling time of the controller equals to the timestep of FEM, T_s = 0.3 ms. The process parameters for the calculations below were adopted from literature [25] for a single layer while a constant scan speed was assumed.

$$BuildTime_{Layer} = {Layer}/{Scan} \quad Speed = {0.001m}/{0.004m/s} = 0.25s \qquad (2)$$

During each time-step k four blocks are produced consisting of 6 cells in the above-given form (1). The hashed data is shown in Figure 4 with all the appropriate data to present.

The total size for each layer can be calculated as:

$$D_{TOT} = TotalBuildTime \times {DataSize_{Layer}}/{BuildTime_{Layer}} \qquad (3)$$

```
=====================================================================================
Block ID: 10100
Timestamp: 12-Jun-2020 15:16:13
KPI: KPI: Temperature
Certification: Certified Control Signal
Certification: Engineer#1
Certification: Crypt. Value
Hash: 1f8768c4bd2aca380197b596b652dbd985a699432cab21970f8122f155ba7de9
Previous Hash: 26b903cf1728de07b30d26292a34f52f6e61b38d2f5913e97a1d330b1d84d92f
=====================================================================================

=====================================================================================
Block ID: 1099
Timestamp: 12-Jun-2020 15:16:13
KPI: KPI: Temperature
Certification: Certified Control Signal
Certification: Engineer#1
Certification: Crypt. Value
Hash: 26b903cf1728de07b30d26292a34f52f6e61b38d2f5913e97a1d330b1d84d92f
Previous Hash: 6e5daebde2913f852a980a8572b272f49dd3969afede5193fa750187ff776acc
=====================================================================================

=====================================================================================
Block ID: 1098
Timestamp: 12-Jun-2020 15:16:13
KPI: Process Parameter: Heat Flux
Certification: Certified Control Signal
Certification: Engineer#1
Certification: Crypt. Value
Hash: 6e5daebde2913f852a980a8572b272f49dd3969afede5193fa750187ff776acc
Previous Hash: 45172f0b33bd1d7ee382ca53d5785f76c8c71dff1381f5d297b668987b55603a
=====================================================================================

=====================================================================================
Block ID: 1097
Timestamp: 12-Jun-2020 15:16:13
KPI: Process Parameter: Heat Flux
Certification: Received Control Signal
Certification: Engineer#1
Certification: Crypt. Value
Hash: 45172f0b33bd1d7ee382ca53d5785f76c8c71dff1381f5d297b668987b55603a
Previous Hash: 595c9f84b1e7f88c9e6aeceb39aa1ccf1b9f7904c5ee42c2abfa0032876a7dbc
=====================================================================================
```

Figure 4 Examples of hashed data

5. Results & Discussion

On the data side, it would be interesting to investigate the respective requirements. The following estimations are very useful towards validating the feasibility of the framework. This is very relevant, as the data have to be kept until the upper-level certification takes place, i.e. certification at the level of the layer or even the part itself. To this end, it is estimated that a single layer may produce up to 1.40 MB of structured data in 0.25 sec. A typically small L-PBF part takes circa 30 minutes, hence a total of 168 MB can be predicted for a single part. Considering a plant with 20 similar machines producing the same component, the data size equals to 3.36 GB produced in 30 minutes. In addition to this, Razvi et al. [26] report that circa 0.5 TB is generated in a single build from monitoring data. Furthermore, another author reports that a total of 600 variables produce about 300 MB logged data per build [27].

It is also useful to measure the computational time in each block creation and the attachment to Blockchain. The response and the measurements are depicted in Figure 5. This way, it would be easy to find out whether some special treatment is needed in the control schema itself. Details are known to affect the efficiency of a controller, and related literature is also existing. In this case, it would be required to have a specific treatment in this schema, as the delays from the four transactions are comparable to the sampling rate. In this case, the controller has been able to successfully encounter this introduction of delays, as the controller that has been used particularly for this case is an H-infinity controller [28].

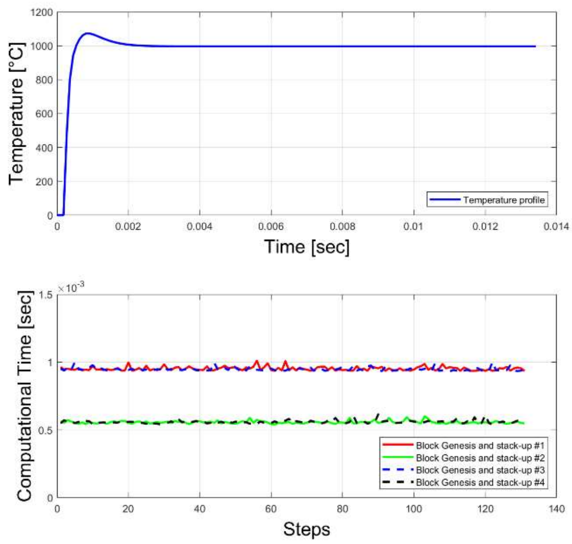

Figure 5 Response & Computational Time

The proposed generic framework suggests that the knowledge from each stage is turned into certified data with the collaboration of an expert agent, such as a high-skilled engineer with the appropriate knowledge of the specific process. Distributed ledger technology allows firms to exchange valuable data within their peers, so the enhancement of the current long-term bet of trustability of data in a firm may be feasible.

The intellectual properties of a firm and especially a small-medium-enterprise (SME) need enhanced protection against digital threads. An added value is expected from the certification of process control and optimization to provide tracking of the transactions for all the nodes/peers of firm while maintaining un-touched. The certification of an agent should guarantee the ordinary operation.

Table 3 Certification of process control

Knowledge Gap		Certified expert agent aspect
1.	Advanced topics in control theory such as robustness with uncertainty-disturbance modelling, optimal control, etc.	Variability in each process with the same design criteria
2.	Delays causing network, sensors, actuators, etc.	Real-time control
3.	Process optimization	Matching control or optimization criteria to manufacturing criteria
4.	Controlling process for different kind of materials such as metals, polymers, ceramics/Different material leads to different defects and deviations	Locating optimal parameters profiles / detecting defects & properties
5.	Repeatability & reliability for accuracy	Control applicability
6.	Unknown properties	Advanced multi-scale modelling / IoT metrology
7.	Quality Assessment	In-situ monitoring
8.	Resources streams & resources productivity quantification (optional)	Link with ERP and PLM systems / Aggregating resources with timestamp / Traceability of parts and resources

Finally, the process control and the optimization of operation should reduce the variability of products with the guarantee of closed-loop response within the design criteria.

Herein, the challenge of a certified expert agent requires a variety of advanced skills. Those skills should bridge the current knowledge gap. In Table 3 a total “course” for a certified employee is proposed.

6. Conclusion & Future Work

A generic framework has been proposed in the current research work implicating Blockchain and an expert agent which turns the knowledge such as process control attributes into certified data for the nominal operation. This seems to successfully (a) provide the certification to procedures related to manufacturing process optimization and/or control and (b) provide opportunities for security. Both are done with sharing the appropriate amount of information to implicated agents, such as certification of control and control parameters to peers and machines, respectively.

As per future work, the industry and academia should establish certain advanced skills regarding the thermal processes for a certified employee, while tests at larger scale should be made, in order to guarantee practical feasibility at larger complexity levels, for instance, in the case of a centralized multi-agent controller that synchronizes many controllers for many different processes and / or machines. In this case, the synchronization of the firmware used ought to be checked thoroughly.

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