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EXECUTIVE SUMMARY OF THE THESIS

Online Synchronisation of Digital Twins: a Control-based Methodology for Manufacturing Systems Applications

M.Sc THESIS IN MECHANICAL ENGINEERING – INGEGNERIA MECCANICA

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ACADEMIC YEAR: 2020-2021

1. Introduction

Under the fourth industrial revolution, several technologies have emerged and contributed to a substantial advancement of the automation and data exchange in the manufacturing field. Parallelly, the competition and uncertainty of the global markets have forced a continuous transformation in production systems. The digitalization of processes and this demanding context has sparked an interest towards the research of Digital Twin (DT). The concept extends from the integration of technologies such as Cyber Physical Systems and Internet of Things, providing the capabilities to improve productivity and support decision-making. In the context of manufacturing, the DT is defined as: *"a virtual representation of a production system that is able to run on different simulation disciplines that is characterized by the synchronization between the virtual and the real system […]. The topical role within Industry 4.0 manufacturing systems is to exploit these features to forecast and optimize the behaviour of the production system at each life cycle phase in real time"*[1]. To develop a DT, bi-directional communication between the system and its digital counterpart is required. The latter is identified in a Discrete Event Simulation (DES) model, given the capabilities of this technology in analysing complex and dynamic systems. In addition, the DT has to be able to represent in real-time the complete behaviour of the physical system and adapt to possible transformations.

The aim of this work is to investigate the concept of "alignment", introduced as the condition of the DT to completely reflect the physical system. An integrated control manages the actions of model update, synchronisation, and input model update; developed to align the digital and physical systems. Markers are introduced as binary indicators which convey information about the convergence of the two entities.

Chapter 2 of the executive summary presents the current state of research regarding the alignment, together with the identified literature gap. The developed methodology and implementation aimed at keeping the alignment condition are described in section 3. The results of the experimental phase are reported in chapter 4, finally a case study is presented in section 5.

2. Problem statement

The effective contribution of adopting a DT, it is the possibility of performing analyses and support short-term decision making during the operational phase. A requirement for this application is to maintain the DT aligned with the real-time conditions of the manufacturing system. Disregarding this complex task may cause multiple levels of divergency between the two entities, leading to erroneous results. Three challenges have been identified, each one of them being a possible cause of misalignment:

- Challenge 1 – Topological misalignment: the topology and layout of a manufacturing plant might vary, together with the functioning logic of the production processes.
- Challenge 2 – Instant conditions: defined by the evolution of the status of the resources during production.
- Challenge 3 – Stochastic behaviors: these replicate the duration of the processes that characterize the real system and are required to be correct when performing predictive simulations.

To tackle these challenges the literature proposes techniques which extend on multiple fronts. The first is resolved by automatic model generation and conversion procedures. These exploit the availability of information coming from the production floor to automate the model design and development phases. The second challenge is addressed by synchronisation techniques. The data provided through processing parameters allows the DT to reestablish the instant conditions present on the real system. Also, to address the third challenge, with the purpose of predictive analyses, it becomes essential to first synchronise and then initialise with updated input parameters. Common considerations among the found techniques are that systems have to be able to automatically communicate between each other and results have to be delivered as soon as possible. However, these solutions focus only on single challenges, so a lack of flexibility is present. In addition, the actions are directly used to address a divergency but no control is interposed to foster efficiency and balance between computational power requested and impact of the results. To overcome this limitations, a new methodology addressing the alignment of Digital Twins must be introduced. It needs to include actions to solve different kinds of discrepancies, and a control to effectively manage their deployment during the operational phase.

3. Proposed methodology

3.1. Overview

The framework develops on multiple elements to maintain the alignment of the real system and the DT. It is assumed that data conveyed by the two systems are always correct but not always available. In fact, only when information is provided by the entities, the divergency between them can be measured and a "synchronisation point" is defined.

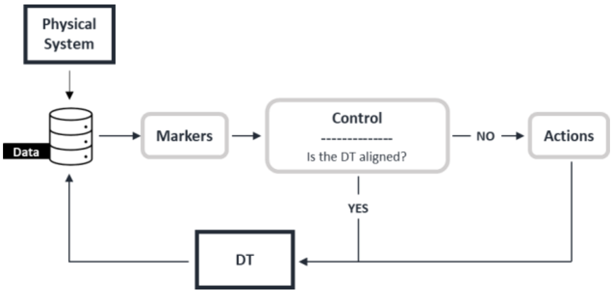

Figure 3.1: Simplified illustration of the developed framework

Real-time raw and derived data from the production system are compared with DT results obtained from the integrated simulation tool. Two validation techniques compute two distinct markers assessing respectively the correctness of the digital model's logic and stochastic behaviors. The third is the result of a synchronisation check and indicates the alignment of instant conditions. All three convey binary values, either confirming or denying the alignment. Following the scheme, a control uses these indicators to decide whether or not to trigger a corrective action.

3.2. Model update

For a discrepancy in the design of the simulation logic and layout a model update is deployed, consisting of two steps. Firstly, a graph model is automatically generated through the discovery procedure developed by Lugaresi et al. [2] is used. Then, the result is converted into an executable DES model by means of an originally developed algorithm using the ManPy library [3]. The graph model features a series of nodes and arc, respectively representing the activities composing the manufacturing system and the connections between them. The conversion process populates a simulation model translating the generated elements into simulation objects.

3.3. Synchronisation

The synchronisation uses the log of the events acquired by the infostructure integrated into the production line. To align the DT's instant conditions the action of synchronisation is deployed. As Figure 3.2 shows the simulation model is given two inputs: the instant initial position of the parts along the system and the stream of processing parameters. Using a classic trace-driven simulation approach the initial positions are forced with those instantly acquired and the alignment is recovered by simulating the trace collected. A final comparison of the aligned instant conditions assures the effectiveness of the procedure.

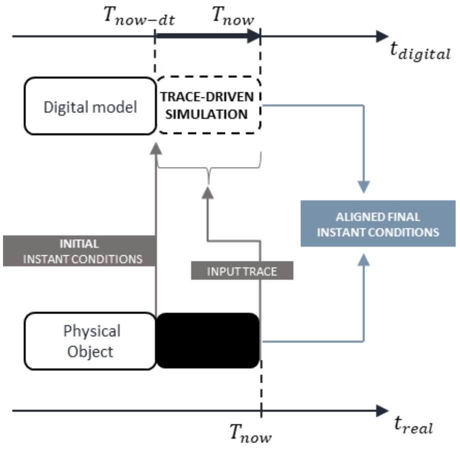

Figure 3.2: Synchronisation methodology

3.4. Input model update

The stochastic patterns are equally affected by the evolution of the production line. To conduct predictions, the information provided within the historical data are used by a distribution fitting function to update the stochastic inputs of the simulation model.
Additionally, the alignment of the digital and the manufacturing system is a mandatory requirement to assure the quality of the contributing services provided by a DT. Monitor the performance of the production system is one of them. An aligned DT provides additional correct information which would be difficultly acquired from the physical counterpart. Forecasts of defined KPIs allow not only to confirm if particular targets will be met, but also are integrated in what-if analyses to purposely support the decision-making process. The contribution of a DT adapting to changes in the production system support the precision of prediction results. These services require the digital model to be backed up by the confirmation that the markers are checked. In particular, to monitor, the logic and synchronisation markers have to be satisfied, while to conduct forecasts all three are essential. Practically, the results of the trace-driven simulation are used to provide additional information to monitor the real system, while obtained final instant conditions are used to initialise the predictive simulation.

3.5. Alignment components implementation

This section illustrates the implementation the developed methodology with the objective of being able to conduct several experimental campaigns and operate with the infostructure provided by a lab-scale model.

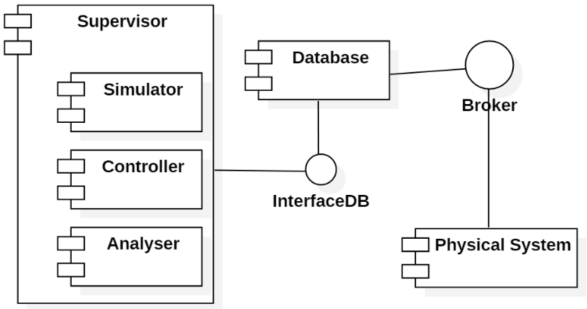

Figure 3.3: Component diagram of the implementation

Figure 3.3 illustrates the architecture and the components, all developed using Python.
The supervisor administers the controller in charge of actuating the procedures of: Model Update, Synchronisation, and Input Model Update based on the markers.
The simulator allows to integrate the digital model generated and converted to conduct Trace-driven and stochastic simulations.
The analyser elaborates the raw data, included in the database in the form of events log, into derived KPIs e.g., system time, inter-departure time and processing time.
A dynamic database is built using InfluxDB, it

stores several categories of data such as: real performance computed by the analyser, digital results obtained from simulations, and the markers.

The Broker interface allows the exchange of information between the physical system and the Database using a Message Queue Telemetry Transport (MQTT) protocol.

The physical system is a two-station lab-scale manufacturing system available in the "Digital Twin lab" at Politecnico di Milano, illustrated in Figure 3.4 The system is built with LEGO MINDSTORMS components. Each station is composed by an EV3 brick, three optical sensors, a motor, and a part entrance system. The EV3 is the controller of the station, by means of a Python code it interfaces with sensors and motors. In Addition, process parameters e.g., processing time, can be determined though configuration settings. The connection between all components is achieved by means of Secure Shell Host (SSH) protocol.

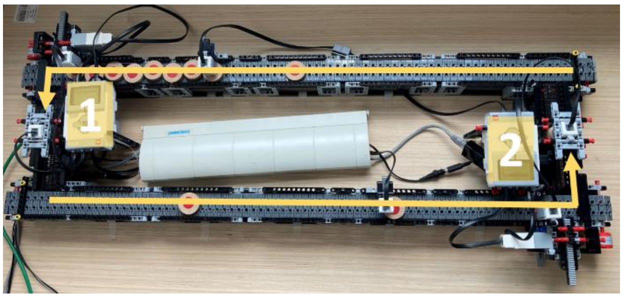

Figure 3.4: Lab-scale model: 2-station closed-loop system

4. Numerical experiments

This section illustrates the results obtained from the experimental phase divided into two stages: in 4.1 the validation of the single components, and 4.2 the test cases.

4.1. Validation

The single aligning actions integrated in the platform are tested to draw the possible limitations and validate the efficacy. The model update process is tested on increasingly complex layouts and logics. A comparison between two digital systems is performed with Arena Rockwell as benchmark. The simulation models obtained have been generated correctly for the listed configurations: a six machine flowline, a parallel servers system, and a two station closed model. Initially, digital results obtained from the executable DES model generated and converted are compared with those attained with Arena Rockwell, particularly using trace-driven and random variate generation approach. Consequently, the synchronisation applied with the lab-scale model is tested and instant conditions are effectively maintained aligned. Also, evaluations on the impact of a missing synchronisation during forecast analyses show a discrepancy on average of almost 10% in the predicted results.

4.2. Test cases

Multiple configuration settings are imposed on the two-station lab-scale model to evaluate results in the context of prediction analyses. Layout and logics as well as instant conditions are assumed as correctly aligned and are constantly checked for the entire duration. Three experimental campaigns are performed, and using ANOVA the significance of the results is evaluated. To isolate possible source of errors, the stochastic inputs have been previously fitted and validated.

The first series of tests aims at demonstrating the effect of aligning the DT during operations on the prediction capabilities. It is investigated by five independent experiments performed by forecasting the overall number of parts manufactured during different production shifts of the lab-scale model. Figure 4.1 illustrates the results obtained, where the prediction error becomes lower and more consistent as the time of forecast gets closer to the end of the production period. The error measures the discrepancy between the production predicted at a particular instant, x-axis, and the actual number of parts manufactured at the 20th min.

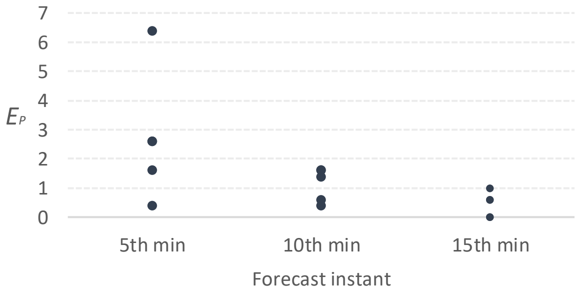

Figure 4.1: Prediction error for different forecast instants predicting production of parts at 20th min.

The second experimental campaign investigates the effect of using a misaligned model in terms of stochastic inputs on the results of the forecast analysis. The results show a significant impact of the mean of the used distribution, while the variance and type are not influential.

The third experimental campaign is aimed at proving that the forecast capabilities provided in a DT framework are able to adapt to unpredictable events. In fact, the time between forecast analyses becomes relevant. The lab-scale model production is set to test five experiments and for each one of them two failures appeared in different moments during the shift. The platform is implemented to test for each experiment different forecast frequencies from one simulation every 5 minutes, therefore 7 analyses in a 40 minute demonstration (first 5 minutes of warm-up) down to one every 40 minutes. Results are summarised by gathering the prediction errors obtained every time an analysis is performed under the same forecast frequency, and compared using a developed error indicator.

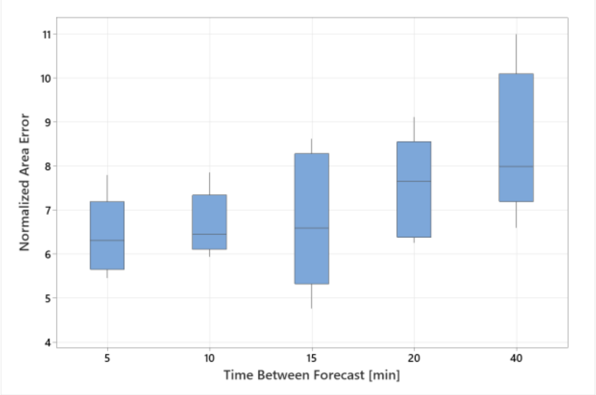

Figure 4.2: Boxplot illustrating the prediction error for the different time between forecasts.

Figure 4.2 confirms the beneficial contribution of a higher forecast frequency to adapt prediction analyses to unpredictable events. In fact, the results obtained at lower frequencies show significantly worse performances. While the result for the higher values do not show a significant difference in terms of prediction error.

5. Case study

A case study is introduced to provide a proof-of-concept Digital Twin of a manufacturing system. For this purpose, the capabilities of monitoring, forecasting, what-if analyses, and feed back action are demonstrated using the same production system illustrated in Section 3.5.

The components explained in the same paragraph are applied, also the Validator and Evaluator are integrated under the Supervisor management. While the first provides the logic and input markers and its functioning is the result of the work developed by Gangemi et al. [4]. The Evaluator component is responsible to detect a degradation event in the manufacturing system, conduct what if analyses and implement the selected feedback action on the lab-scale model. In particular it tests two possible alternatives:

- Scenario 1: Keep producing at a slower pace and repair the machine at the end of the shift.
- Scenario 2: Stop the plant to allow repairing activities and then continue with the original production pace.

The evaluator component is in charge of detecting disruptive events that modify the stochastic behaviour of the system. The performances before and after the event are compared, and if they are significantly different a what-if analyses is performed. The pre-determined scenarios are simulated and the most productive in terms of parts produced by the end of the demonstration is implemented to the lab-scale model

During the demonstration, the functioning of the components is proven. Initially, the two-station system is started, and the simulation model is automatically generated and converted. Afterwards, the analyser illustrates in Real-time the performance computed by the physical system. The alignment of the instant conditions is assessed through the digital results obtained in Real-time by the simulation model. The comparison between the real and digital performance is shown in Figure 5.1.

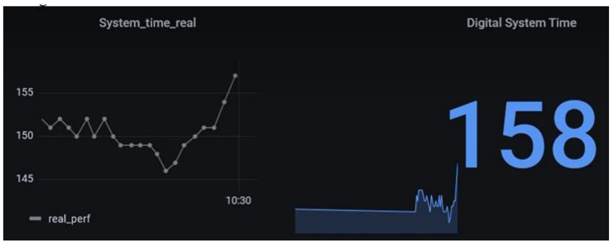

Figure 5.1: Illustrative comparison between real and simulated system time, proof of the aligned instant conditions. Data visualization tool: Grafana.

The ability of providing additional information which makes the monitoring service useful is proven to be effective. In fact, a shift in the utilisation of the two stations, shown in Figure 5.2, highlights the degrading impact of the event happened.

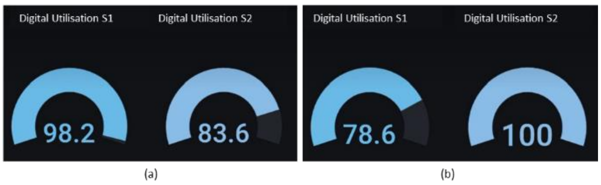

Figure 5.2: Digital utilisation for station 1 and station 2: (a) before, (b) after the disruptive event.

In conclusion, the evaluation of the two scenarios results in a forecasted number equal to 221 parts produced for scenario 1 and 228 for scenario 2. The latter is therefore applied, corresponding to an increase by 3% in performance.

The proposed case study allows to assess the capability of the control in maintaining the DT aligned with the manufacturing system. The procedures of model update, synchronisation, and input model update have performed effectively. With the introduction of the Evaluator and Validator components the DT services of monitoring, forecasting and what-if analyses have been provided.
Additionally, the bi-directionality demonstrated asserts this framework as a proof-of-concept Digital Twin.

6. Conclusions

This work addresses the alignment between a production system and its Digital Twin. A methodology is developed addressing the challenges causing misalignment. With a control, the actions of model update, synchronisation, and input model update are managed. This framework enables the monitoring and forecasting services, aiding in short-term decision making.
Additionally, the efficiency is increased by the introduction of markers, indicating the alignment status, and determining the deployment of the actions.
The main limitations of the proposed techniques are the difficulty of implementation in complex production systems. Additionally, data acquired from the physical plant is required to be complete and correct.
Future developments shall investigate the implementation of more precise comparison procedures and corresponding corrective actions, providing more effective and precise results. The methodology could also be furtherly tested, by experimenting on real scenarios more complex systems.

7. Bibliography

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