Modeling and simulation of mechatronics equipment for a Digital Twin-enabled demonstrator

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Abstract— **As for many sectors both in the industry and research world, the trend towards a deep grade of digitization of mechatronics systems is ascending considerably year after year. Advantages of digitization are manifold, going from the possibility to test real-case scenarios with cost-effective simulation tools, to the chance to control and optimize real systems by means of their virtual replicas. As a result, enabling technologies such as Digital Twin are in their prime of development. This work intends to contribute to research in this field with a successful application case in a laboratory environment. Scope of this work is the modelling and simulation of a transfer line, along with the mechatronics equipment operating on it. The simulated system will complete the functionalities and potentialities of the virtual replica of the line in the framework of a DT-enabled demonstrator. Limitations and future improvements are also highlighted.**

I. INTRODUCTION

The manufacturing and automation sectors have undergone significant changes in recent years, driven by the demand for highly variable products together with an increasing complexity of manufacturing systems and automation tools [1]. Concurrently, advancements in digital technologies have led to transformations in product integration phases throughout their lifecycle, underscoring the importance of establishing up-to-date digital representations of systems' equipment [2]. This shift towards modern manufacturing practices, often termed as smart manufacturing [3], represents one of the prevailing trends today. Among the technologies facilitating this transition, the Digital Twin (DT) stands out as a pivotal link between the physical and digital realms [4]. The development of DTs enables efficient updates on the status of automated systems in manufacturing and facilitates real-time prediction, control and optimization. As a result, research in this direction has experienced a significant spread all over the world: simulation techniques, to replicate automated systems in the virtual world, have proliferated, offering researchers and not only the possibility to give a positive boost to explorations in the field [5]. It is however important to underline that significant limitations in the creation of DTs are common, due to the fact that achieving a reliable real-time synchronization with reality still constitutes an open challenge. This comes as a consequence of different factors, e.g. limitations in commercial closed systems mutual communication, limitations in software simulations' capabilities, exc. [6]. However, latest advancements in the field seem promising for future developments.

Means: modelling and simulation of a product line = DT ! ?

This is where this work comes in, presenting a successful example of digital modelling and simulation applied to the mechatronics equipment of a laboratory environment. In particular, a small-size transfer line constitutes the object of this study: the model of the line, along with the machines which operate on it, is created thanks to a physics-based 3D simulation software. Simulation runs are performed in order to validate the developed Digital Model (DM). Moreover, the synchronization with the real line is performed by syncing operations of the real and the virtual system via REST API communication. Outcome of this work will be the establishment of a fully synchronized real-virtual automated system, which serves as a successful case of DT-enabled demonstrator. Details regarding the role of the DT framework in system's operation are provided throughout the paper and conclusions about its limitations and future potentialities are drawn.

Section 2 reports the methodology which will be followed to pursue the objectives of this work, while Section 3 highlights the expected late-breaking results and some considerations about what is expected to be achieved. Section 4 concludes this work with outlook for future improvements and additional study.

II. METHODOLOGY

A. System description

The system under investigation in this study is a versatile and intelligent transfer line, designed and manufactured by Montrac®. It is currently installed at the Smart Mini Factory (SMF) laboratory of the Free University of Bozen-Bolzano [7,8]. This transfer line consists of two main rail loops, seven workstations, two switches and three shuttles, all intended to function as transportation components in a prospective assembly line employing DT technology. Within the transfer line setup, there are currently two robotic manipulators in operation. One is a parallel industrial robot (Adept Omron 4), while the other is a 6-joint industrial collaborative robotic arm (Universal Robot UR10) equipped with a two-finger gripper as end-effector. The layout of the transfer line in the laboratory is partially shown in Figure 1, with the foreground showcasing the two switches connecting the central and larger rail loop with the secondary one. Positioned within the main rail loop, the industrial collaborative robotic manipulator UR10 serves two mirrored workstations and a warehouse. Additionally, the warehouse is accessible to the parallel robot, along with an additional workstation located beneath it.

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Figure 1. Transfer line arrangement in the SMF laboratory

The track rail has been sketched in three separated paths for specific modelling purposes, which will be described in the next sections. As a result, the main loop constitutes the main track; another part of the track is given by the outer loop, on which two additional workstations can be utilized; the last track part is that served by the switches, which can be chosen to move shuttles along the main loop when the outer loop should not be used.

B. Digital Model

At the current status, the replication of the transfer line into the digital environment has already started. While there are numerous simulation tools available, the software selected for this study is called iPhysics. The decision to utilize iPhysics was influenced by its 3D physics-based nature, which allows users to kinematize multibody systems while exerting direct control over their relative movements and constraints, including translations and rotations. Furthermore, the software offers comprehensive capabilities for generating and describing the dynamic behavior of rigid bodies, making it a suitable environment for this study. iPhysics tool allow indeed to utilize static, kinematic or dynamic objects. Moreover, the internal language of iPhysics allows to exactly model and control the motion of such objects by manipulating a set of variables directly associated with them.

C. Digital Twin

To embody this perspective of a DT-enabled demonstrator, the conceptual framework and data flow have been organized as follows. The conceptual structure comprises a DT application layer, which supervises the collection of information from the physical environment and the assignment of tasks, adhering to manufacturing rules and constraints. The gathered information is stored in an open database accessible by both virtual and physical entities within the system. The distinctive feature of the designed system lies in the simultaneous dispatching of tasks to both the physical environment and its virtual counterpart. This is made possible via REST API communication, which enables to read signals and assign values to controllable variables in iPhysics. A prerequisite is to start from the same exact configuration, both in the real and the virtual world, e.g. with the shuttles at the right workstations, exc.

III. LATE-BREAKING RESULTS AND DISCUSSION

A. Digital Model

Specifically applied to the case of the transfer line in exam, the DM should encompass the switches and shuttles' movements and the operation of the two manipulators. The DM created in iPhysics is completed at a graphical level, as shown in Figure 2.

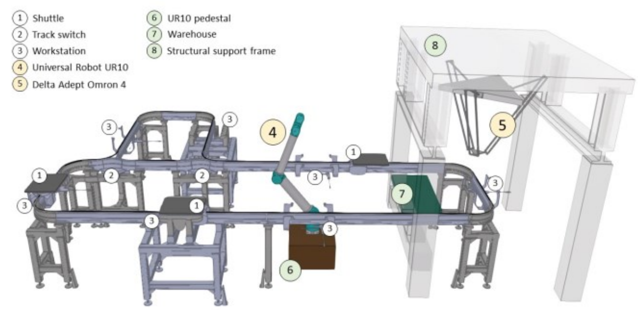

Figure 2. Transfer line DM with mechatronics equipment in iPhysics

From a modelling point of view, the DM is in development: some objects are already fully modelled but some others still lack for model specifications of their parts. Table 1 shows a list of the objects defined in the virtual environment of iPhysics, along with the status of their model development.

TABLE I. MECHATRONICS EQUIPMENT OVERVIEW

Object	**Typology**	**Stage of modelling**	**Done / to be done**
Line structure	Static	Fully modelled and validated	Track rail paths fully defined by three different sketches
Switch (X2)	Kinematic	Fully modelled and validated	Collision detection with shuttles
Shuttle (X3)	Dynamic	Partially modelled	Dynamic behavior to be adjusted, i.e. deceleration near workstations before completely stopping and waiting time at the end of main track before path choice
Robot UR10	Dynamic	Not yet modelled	Kinematic chain to be defined
Robot Adept	Dynamic	Not yet modelled	iPhysics does not include this type of robot in the default library – currently modelled by hand

The correct functioning of the DT layer to achieve a fully synchronized demonstrator status relies on the correct replication of mechatronics equipment operation along the transfer line. Starting from the two switches, a collision detection function has been implemented to detect when shuttles are running on them or not. Moreover, a logic script has been written in order to command the shuttles to move along switches track rail path when the two workstations of the outer ring of the line are not to be reached. In this way, shuttles

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are commanded to follow the shortest path to reach the workstations on the main track, if not differently instructed.

Regarding the shuttles, their movement control logic is of great importance for the synchronization between the real and the virtual system. This logic among the different workstations is in an advanced modelling stage, but still lacks some refinements, as specified in the previous section. Expected results in this direction will be twofold: first of all, the braking of shuttles right before reaching one workstation should be simulated, in order for the movements to be fully synchronized. Lastly, a required stop before being told whether or not to proceed on the switches track path still needs to be encompassed. At the current status, shuttles move along the rail paths with constant velocity and a small deceleration before stopping. A further improvement could be to install sensors on the shuttles to precisely measure their velocity, acceleration and deceleration.

For what concerns the robotic manipulators, the first important step to be followed will be the definition of their kinematic chain in the software. This operation might result simple for the UR10, but it is not so for the Adept Omron Quattro since it is not present in the default library of the software. A second step will be the replication of a desired operation cycle of the transfer line. This could lead to explore three different roads: the first possibility is to faithfully replicate the operation points and tasks of the robot manually, which could prevent software system errors, but which require a significant modelling time. The second path that is currently being explored is the possibility to directly integrate an external robot program to the software, which could significantly reduce the workload of creating it from scratches. Another idea might be to exploit REST API communication to read robots' positions real-time and communicate them to iPhysics layer. This possibility seems promising and interesting, but a strong limitation could also be represented by time delays affecting the communication.

B. *Digital Twin*

In conclusion, as the virtual environment will be modeled to accurately replicate real-world behavior thanks to the completion of the steps above described, tasks assigned to the virtual realm will be executed with provisional adjustments to manufacturing parameters. This will enable the DT layer to explore various approaches to task execution through the 3D simulation module. In this setup, tasks delegated to the physical realm are executed while simulation runs seek potential enhancements. On one side, freely running the simulation as it should be in the virtual world and comparing it with the real operation can lead to the identification of errors, not expected waiting times and room for improvements. On the other side, by leveraging data collected from the real world and simulation outputs, the DT layer will be able to dispatch refined tasks. This would complete the fully synchronized functioning of this DT-enabled demonstrator. The outcome framework, together with a specification of how the communication among the layers works, is depicted in Figure 3.

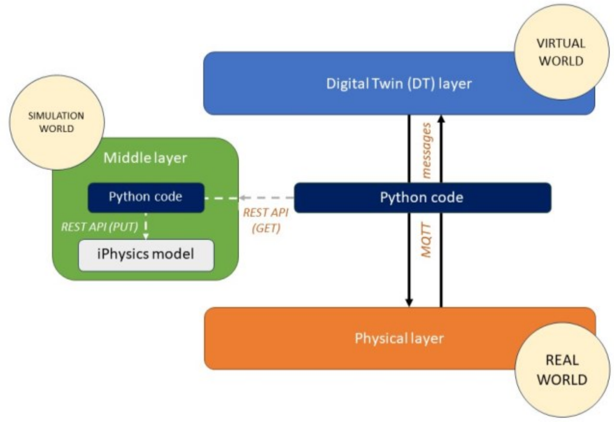

Figure 3. Framework and subdivision of layers in the DT-enabled demonstrator

IV. CONCLUSIONS AND FUTURE OUTLOOK

This work intended to provide the reader with an overview of preliminary results related to the modelling and simulation of mechatronics equipment for a DT-enabled demonstrator. This demonstrator involves the exploitation of a small-sized transfer line in a laboratory environment, on which three shuttles move. The system in exam has been described in its entirety, together with specifications regarding the different machines operating along it. Moreover, an insight into the stages of modelling of the different objects in movement of the line has been provided. Details about the role of the DT in this work have also been specified. The authors concluded with future adjustments, improvements and steps which could make this study complete.

Even though the presented results still lay at a preliminary stage, authors believe that the contribution of this work to the research in the field can be of interest to many researchers. The creation and usage of a DT-enabled demonstrator, although utilized in a small-size context, can indeed provide useful insights into limitations and potentialities of such technology. A possible adaptation to other systems in the same laboratory or the eventual inclusion of more machines operating along the line into the DT layer will be also explored in future work.

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