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Creation of a micro cutting machine tool digital-twin using a cloud-based model-based PLM Platform: first results

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Abstract

The current work presents the first results when aiming to create a digital twin of a single edge micro cutting machine tool in a collaborative cloud-based PLM platform. As starting point, this work takes the models created during the development and design phase of the machine tool, which date back to ongoing works that started three years ago. In order to mirror the physical device in a unified platform, the different models, created using different computational applications, have to be imported into a single collaborative PLM platform (3D Experience from Dassault Systems). The goal of integrating these models into a unified cloud-based platform is to achieve an interoperable model-based digital twin. The digital twin should allow to estimate and simulate the behavior of the machine under different cutting process conditions. Ultimately, it should also allow to estimate how the machined part will be. The PLM platform is the kernel to implement a closed-loop data flow between the digital and the physical domains.

Keywords: Micro Manufacturing; Digital Twin; Cloud platform PLM; Single Edge Micro-Cutting.

1. Introduction

The digital twin concept comprises the integration of product development and design data with data from the physical product along its lifecycle. A digital twin can be seen as the digital representation of a specific physical product, in the form of computational models, identified by its serial number, at a specific point in time, and with sufficient fidelity to simulate the corresponding physical product [1]. The concept of cyber-physical systems (CPS),

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which comprises the integration of computation with physical processes, is also connected with it. The concepts of Cyber-Physical Production Systems (CPPS) and Cyber-Physical Machine Tool (CPMT) were already coined [2-3]. The former is a wider concept and it refers to integrating production processes and resources design and real time data into a cyber-space to assist in predictive and decision-making tasks. The latter refers to the integration into such context of machine tools. The achievement of a CPPS requires the integration of the CPMTs that conform the production system. The digital-twin is an enabler of it and for its creation a software framework is needed.

Product Lifecycle Management (PLM) platforms provide a software framework to manage large amounts of data generated in the various phases of a product lifecycle. The last generation of collaborative cloud-based PLM platforms facilitates the realization of the digital-twin concept. First, by means of the digital integration of processes and models, and second, by serving as a source of true product related data across the entire product lifecycle [4-5].

Within the context of cutting machine tools, the virtual machine tool concept [6] is clearly the antecedent to the current digital twin and CPMT concepts. Usually, the creation of a virtual machine tool requires a wide variety of software applications to create models and simulations, the interoperability and integration of them is an issue [6]. Although from the conceptual perspective, the vertical and horizontal integration is widely acknowledged and discussed [1-3], the issues arise when conducting an implementation. This paper presents the preliminary works when aiming to create a digital twin of a micro cutting machine tool.

A hybrid six degree of freedom (6DOF) micro cutting machine tool was designed as an alternative to the more complex traditional micro-milling technologies. The machine tool consists of a combination of a parallel mechanism (3 Parallel-Revolute-Spherical - PRS) and a traditional X-Y stage, plus a rotational C axis which enables the orientation of a single edge cutting tool. The advantages of using a parallel mechanism is the high rigidity of its structure [7] which reduces vibrations, and therefore, it helps improving the surface finish of the machined geometries [8]. In order to estimate and validate the behavior of the machine under the cutting process conditions, the creation of a machine tool digital twin is aimed, and it will be used to conduct micro cutting process simulations. There are many available tools and methods for the creation of models and simulations of micro-scale cutting processes [9], all these methods require a different software applications to calculate or estimate a characteristic of the machine being designed [10]. One of the problems of using a diversity of software applications is that the different created models are disconnected, which impedes the creation of an integrated model-based machine tool digital twin. The digital twin of a machine tool should comprise different integrated models to complete its design and estimate its behavior [3],[11].

This work presents the first results when aiming to create an integrated multi-model machine tool digital twin. The selected collaborative cloud-based PLM platform is 3DExperience, which unlike other commercial platforms, which are still based on the use of files, provides an object-based database. An object-based database stores the created objects and their relationships, which helps to achieve the interoperability among different objects and models. The platform is used to create the digital twin of the machine with the aim of performing micro machining process simulations. The simulation results such as torques, driving forces, deformations, strain and stiffness of the device must be compared with experimental results measured in the physical machine. From the comparison of both results is possible to understand and evaluate how much of identical the digital twin and the physical machine are. The next section provides a review of the state of the art. Section 3 shows a description of the physical machine and the created models. Section 4 discusses the creation and current state of the digital twin in the collaborative PLM platform. The paper ends with the conclusions and future works.

2. State of the Art

The introduction of a paradigm shift by Industry 4.0 has been driven by the current need of fusing information and communication technologies with manufacturing processes. The cost reduction in sensor manufacturing, the development of internet-based industrial communication protocols and the increase of computing power have facilitated the integration of such systems [1-2]. The growing interdisciplinary approach to manufacturing and the need of a streamline flow of information has become more critical [2]. The advantage of having a full panorama of the product life cycle is a desired feature in modern industry, long and iterative production processes are enriched by the interconnection of machines, data systems and industry's know-how, all available in one accessible platform focused on delivering the best possible product, maximizing the available resources which leads to an improved design methodology [11]. In order to have each phase, which leads to a finished product, mapped, described, analyzed and improved, it is necessary to have a interoperable knowledge hub. This hub can be described as an framework that contains the fundamental components linked via digital technologies to its core characteristics, this framework should allow the implementation of the Digital Twin concept [1,4,[12],[13].

In the manufacturing context, the Digital Twin is a virtual representation a machine or a specific device which has a task within the manufacturing process, this digital representation is fed by real data from the process and the machine itself [14]. The data are used in models to execute simulations, the results can be interpreted as an output which can be send back to the physical device as a feedback to enhance its performance. Data processing techniques based on heavy computational operations such as artificial intelligence, machine learning, deep learning among others can be implemented within the Digital Twin context, this improves the process models and allows to have an extra degree of control, which can be translated in shorter design/production times [14]. In the industry, the concept of Digital Twin is interpreted and implemented with different degrees of integration, in general, it must represent a physical device, mirroring its characteristics and capabilities, focusing on scalability, interoperability, expansibility and fidelity [15], every industry has different physic models, sensors and flow of information, from which the integration of the different branches will depend on the data flow [16].

The flexibility introduced by the Digital Twin outlines the approach of the new trends in planning, testing and implementation of new technologies on different fields of manufacturing [17]. For instance, in machining processes the sharing of information is crucial, and it helps to analyse the machining tool performance and reliability [18]. The virtual representation of the machine can help to evaluate the degradation of components and prevent catastrophic malfunctions due to their wear [19], also to identify crucial failures and to improve the maintenance procedures [20]. The implementation of the Digital Twin concept is not limited to new devices, a Digital Twin can help to enhance the functionality of old machining devices, by means of applying a reconditioning strategy it is possible to extend the life span of old machinery and in some cases increases its performance [21]. The application of the Digital Twin concept in micro machining processes requires to take into account process related and machine related aspects and models. For instance, the characteristics of the machine tool, the technology used for machining, the machined material, the applied mathematical models and the measurement of the different elements of the machine and process [22].

Industry 4.0 has also an impact in the evolution of cloud-based PLM platforms. Cloud-based PLM platforms allow integrating information systems, engineering procedures, communications and simulation within a unique unified environment, which is a great advantage when aiming to achieve interoperable model-based Digital Twin [23]. Having a centralized collaborative interoperable environment, where all the data of the different stages of the product lifecycle are available, helps reducing the development times and optimizes the data flow, which ultimately should lead to the reduction of costs [24]. Having a Digital Twin implemented in a cloud-based PLM platform is the natural next step in the integration of machine tools in the new dynamic of collaborative and data sharing on the Industry 4.0. In that direction, Dassault Systems (DS) provides its cloud-based collaborative PLM solution, “3D Experience”, as the platform that integrates applications to achieve the implementation of model-based digital twins, e.g.: CATIA Functional Part Design, CATIA Assembly Design, DELMIA Equipment Design, CATIA Functional and Logical Design and Dymola Behavior Modeling.

3. Hybrid 6 DOF micro cutting machine

The increasing demand of precise geometries in the field of micro manufacturing inspired the creation of a single edge micro cutting machine that competes against micro milling solutions. The designed machine is a hybrid 6 DOF device and consists of a 4 DOF tool head and a 2 DOF XY cartesian stage. The tool head is composed of 3 PRS identical kinematic chains plus a rotational C axis (3PRS+C) in conjunction with a X-Y stage, which compensate the parasitic motions of the tool tip and increases the workspace of the machine tool. The entire mechanism has a position uncertainty of ± 3µm. This approach required the development of a new single edge cutting model, which can predict the cutting forces within a range of ±10% of the measured values along the cutting path of the tool [25]. The machine is controlled by means of the Fagor 8070 CNC unit, which supports three communication protocols: Ethernet TCP/IP, Sercos and CanOpen. Sercos is a drive bus, that provides a synchronous connection of the motor servo drives systems with the control unit. CAN Open is used to communicate the control unit with an oscilloscope. The oscilloscope is used to monitor axes displacement, speed and acceleration. Ethernet TCP/IP will be used to transfer data from the machine to the PLM platform.

The machine was designed to incorporate several sensors, which provide the inputs to the control system and the created models. The capacitive position sensors define the limits of the working area, and they are positioned on each translational or rotational axis. Kistler dynamometers, placed on the tool head of the machine, are used to monitor the forces and torque produced in the cutting process. An ad-hoc designed artificial vision system is used to locate the tool tip and make the proper corrections in the cutting path (due to defects in the tool manufacturing, geometry or tool wear) [26]. An overview of the machine is shown in the Fig. 1.

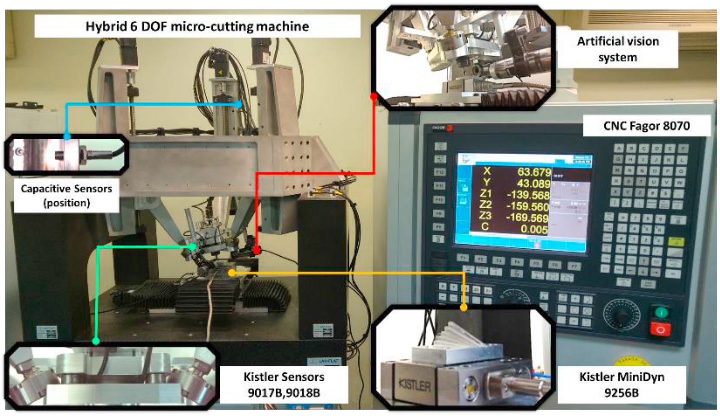

Fig. 1. Hybrid 6DOF micro cutting machine tool.

The development and design phase of the machine tool date back to ongoing works that started three years ago. The initial development context was heterogeneous in terms of the hardware and software applications used. The heterogeneity involves several platforms, processing/capturing devices, programming languages and communication protocols. Fig. 2. shows the main components of the initial development framework and the top-level communication among them. Several models of the machine tool were created. Models may have as inputs data from sensors of the machine, or the output of another model. The models created when the machine was designed and implemented can be categorized into four basic types: geometric model, kinematic model, dynamic model and cutting model.

3.1. Geometric models:

These models are used to predict mechanical interferences of the different components of the machine, both among them and with the machining assembly. A machining assembly comprises the stock material, the fixtures and the final part. An assembly of the machine comprises a set of subassemblies. The machine assembly comprises the 3D solid representation of all its mechanical elements, their relative positions and positioning constraints. The assembly model constraints the limits of the machine tool movements. The dimensional limitations of the machine are dictated by its requirements. In this case, the top-level requirement was the machining of 3D free forms within a micro dimensional range. The working volume of the machine in the XYZ axes is: 155 mm x 160 mm x 190 mm.

3.2. Kinematic model:

The kinematic model contains the definition of the different joints and interfaces, limit positions of the tool head, maximum speed and acceleration of each axis, singularity configurations and home positions on each axis. The details of the kinematic model and analysis are shown in [25]. The kinematic model is used to implement an inverse kinematic process. The position of each axis is determined from the position of the tool tip. Using the data from the vision system, a tool path correction can be applied to compensate deviations in the tool geometry, due to both manufacturing uncertainty and tool wear [26]. Cutting speed, deflections, geometry corrections and target positions are the inputs to the developed model to estimate the tool tip position. The axes stroke ranges between 0 mm and -190 mm for the Z1 to Z3 axes and between -50 mm and 50 mm for the X and Y axes. The Euler angles α and β range between ±30º.

3.3. Dynamic model:

The dynamic model was created to estimate the deflections of the mechanical structure under cutting conditions and the uncertainty in the positioning of the Zi axes. Both structural deflections and positioning uncertainty affects the tool tip positioning. Due to their relevance at the start of a movement and in direction changes, inertial forces were considered. The dynamic model comprises the stiffness of each component to estimate the machine structural stiffness. The stiffness of the machine depends on the position and orientation of the cutting tool in the work space [25].

3.4. Cutting model:

A mechanistic model was developed based on the characteristic of the single edge cutting process. Using Aluminum 7075-T56 as material, experiments were conducted to obtain the specific cutting pressure coefficients with several combinations of cutting depth, cutting width, inclination, position and cutting angles. The model depends on the geometric conditions of the cutting tool, by design, the machine keeps the cutting conditions constant. This is achieved by keeping fixed the position of the tool and the desired depth and width of cut along the tool path. The developed model can predict the cutting forces under these conditions, which are compared against the measured forces [25].

3.5. Models integration and communication

The original development demanded the definition of the interface among the different models and the machine sensors. Fig. 2 shows the original configuration and the top-level communication. A PC was equipped with a data acquisition card and LabView to process the data from the dynamometers. The force data were transferred to a second PC, where the kinematic, dynamic and cutting models were developed in MATLAB and where the artificial vision system was also implemented. A development that implements the inverse kinematic process was done in MATLAB to generate the ISO code to command the machine. The CAD/CAE solutions were installed in a third PC, where the CAD files were stored. The native CAD files were converted into STL files, which were used for the kinematic simulations and to calculate the tool paths.

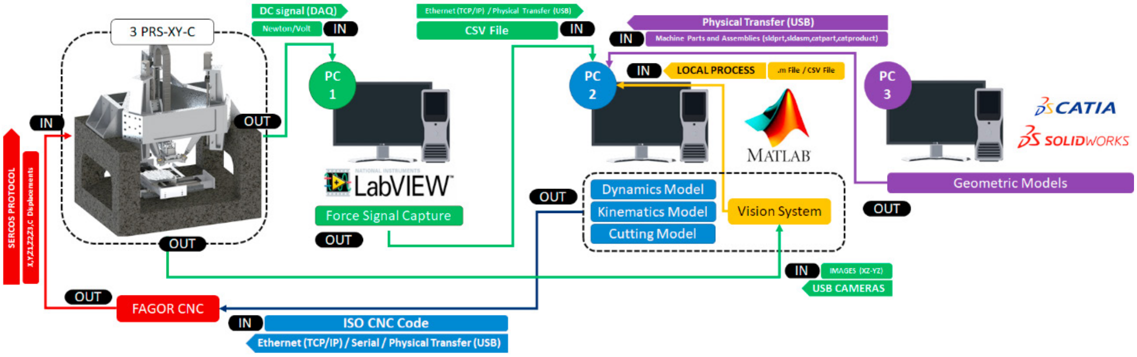

Fig. 2. Original models integration and communication.

The original context was not ideal for the creation of the model-based digital twin of the machine. The main drawbacks relate to the limited interoperability of the acquired data and the difficulties in integrating mathematical models and sensor data acquisition systems implemented in different platforms. Such a context makes hard to integrate the simulations results with the process in a streamline manner. As a consequence, it was decided to initiate the integration of the developed models and machine data communication into a cloud-based model-based PLM platform.

4. Cloud-based collaborative model-based PLM platform integration

The aim is to generate a digital twin of the physical machine in the PLM platform provided by DS (3DExperience). As it was previously mentioned, a digital twin can be seen as the digital representation of a specific physical product, in the form of computational models, and with sufficient fidelity to simulate it [1]. The concept itself is still evolving and in some cases refers to the creation of an ‘as built’ model of the product [4]. The creation of an “as built” model requires the use of reverse engineering techniques to create digital models from the physical components. This work adopts the former approach. With this idea, and from a top-level perspective, a first task is to integrate the existing models into 3DExperience. A second task is to define the machine as a manufacturing equipment. A third task is to develop additional functional and logical models to incorporate the sensors and control of the machine. A fourth task is to communicate the control unit of the machine with 3DExperience. A fifth task is to create process simulations.

The integration of the original 3D geometric models from CATIA v5 and SolidWorks was a quite straightforward task. Although the three systems have different geometric kernels, DS provides a native conversion of data. Models from CATIA v5 and SolidWorks were imported and transformed into 3DExperience native geometrical objects. The result is the 3D ‘as design’ model of the machine components and assemblies. The kinematic and dynamic models created in MATLAB SimMechanics were exported to an XML file. The XML file contains both the semantic of the models and the data of the created models. The XML file was then imported into the PLM platform, but the semantics of both systems are not fully compatible. As a result, using the application Dymola Behavior Modeling, it is necessary to redefine many of the parameters of both models. Basically, only the structure of the kinematic model is properly imported. Some of the parameters that need to be redefined relate to components’ material, material properties, clearances, friction coefficients, inertia data, kinematic joints. The use of the Functional Mock-up Interface (FMI) as a possible alternative to facilitate the integration of the created models into 3DExperience is the alternative to evaluate.

Using the application DELMIA Equipment Design is possible to define the machine as a manufacturing resource. The initial imported kinematic model needs to be completed, e.g.: home positions, axes stroke, mount points. The kinematic model contains the mechanical relations of the different parts and sub-assemblies that form the machine tool, these elements are defined by engineering connections derived from the MATLAB kinematic model. The Fig. 3 shows the different sections of the machine definition: engineering connections, joints, commands, behaviour.

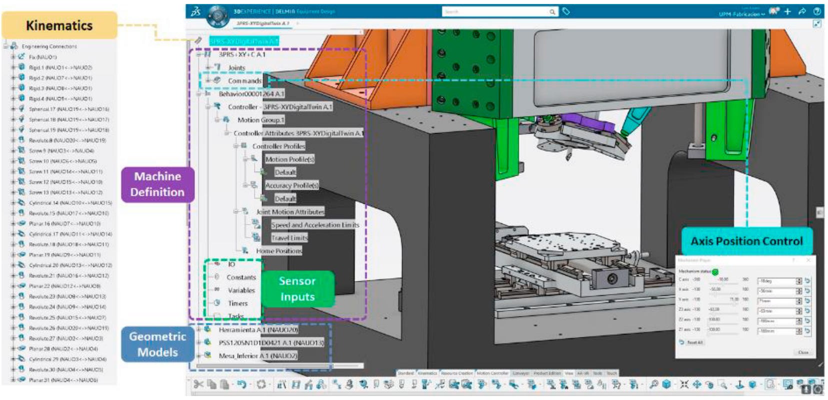

Fig. 3. Digital machine tool integration in 3D Experience DELMIA Equipment Design.

One important part of the digital twin creation is the communication between the digital instance of the machine and the physical device. The communication is bidirectional and comprises, transferring the data collected from the sensors to the PLM platform, and sending the machine commands to the CNC controller from the PLM platform. The positioning data from the end and middle points of the axes are obtained from the installed capacitive sensors, the real time axis positioning can be obtained from the CNC controller. At the moment, two options are considered. One alternative is to collect the data directly from the PLC, this alternative requires the interpretation of the CAN protocol into the 3D Experience Platform. The second option is to obtain the data from the build-in oscilloscope of the CNC controller. In the oscilloscope, a maximum of four variables can be monitored and recorded. The data are recorded in a file .MAT, this acquisition route requires that the CNC controller is configured to share the memory unit used to store such data via Ethernet. The tool tip position obtained from the vision system is integrated in the kinematic model and there is no need for extra processing, in future extensions of the digital twin, this data can be made available for online supervision. The force acquisition is made with a National Instruments DAQ, this data can be stored in an online data base and be accessed from the PLM platform via an ad-hoc development. As part of the machine enhancement, an additional X-Y stage is planned. This stage uses piezo electric actuators to make more refined compensations. The actuators have Nano metric resolution, which greatly increases the precision of the obtained geometries, the control of this actuations can be implemented in an expanded kinematic model in the platform. Fig. 4 shows a top-level view of the digital twin outputs and inputs in relation to the physical machine.

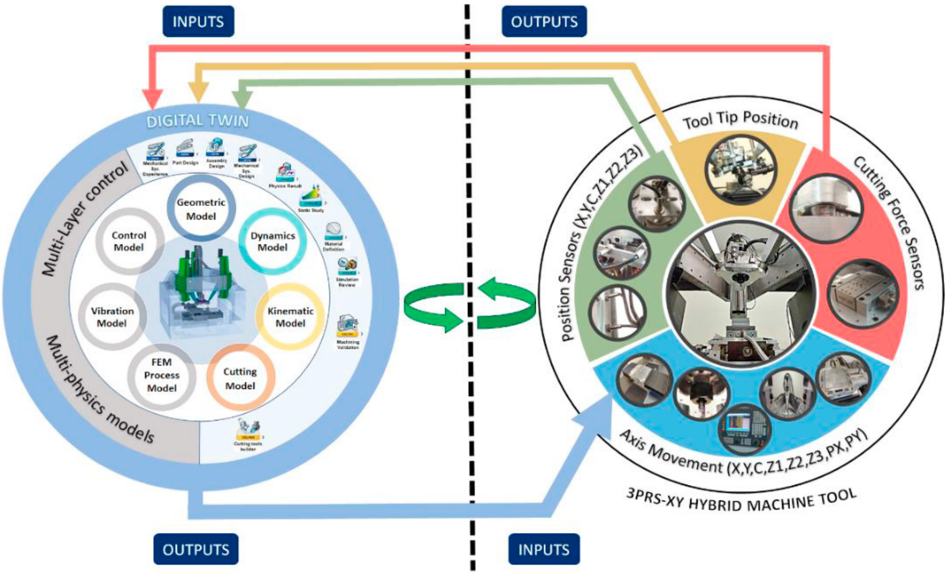

Fig. 4. Top-level view of the planned digital twin using the collaborative 3D Experience PLM platform.

5. Conclusions and discussion

This paper presents the first results of an ongoing project dealing with the creation a digital twin of a micro cutting machine tool. The creation of the digital twin, in a cloud-based collaborative model-based PLM platform (3DExperience), should allow integrating the original models, created using different software applications, and involving different types of communications. The first conclusion of this work is that the integration of existing models is complex and requires a significant amount of rework. As it was expected, the integration of the native 3D geometric models was not an issue. However, the integration of the kinematic and dynamic models demanded redefining many of the constraints and data included in both models. The evaluation of the Functional Mock-up Interface (FMI) is a pending task. The integration of the original models into the new platform is hampered by semantic interoperability issues. The communication protocols available in the CNC controller also make the task difficult, demanding an extra layer of processing in order to make the data available into the could-base PLM platform.

The migration of existing models and data to cloud-based model-based PLM collaborative platforms, as a new trend promoted by the Industry 4.0 implementation, is gradual, and the investment of time and resources is mainly due to data interoperability and data communication issues. The overall conclusion is that the new modeling and simulation capabilities provided by the 3DExperience platform make the necessary effort worth.

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