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Using In-Process Workpieces and Asset Administration Shells for Chaining Machining Skills

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Abstract

This paper presents a comprehensive approach to integrating in-process workpieces (IPWs) within skill-based manufacturing frameworks. Skill-based approaches allow for flexible production setups, with capabilities used to align product requirements with machine capabilities to create suitable production plans. However, accurate simulations of these plans require precise input data, specifically the actual state of the product, necessitating the use of detailed 3D models rather than simple bounding boxes. This research demonstrates how the concept of IPWs, commonly used in CAM-based manufacturing, can be adapted for skill-based production. IPWs facilitate the tracking and transfer of the current state of the workpiece throughout various machining skills, ensuring accurate feasibility checks and error-free execution. The proposed method leverages the Asset Administration Shell (AAS) to manage and exchange data, including IPWs, across different stages of production. A prototype implementation illustrates the feasibility of this approach, highlighting its potential to enhance the accuracy and reliability of production processes. The findings indicate that while the integration of IPWs is promising, further research is needed to address challenges related to collision simulations and the embedding of additional intelligent manufacturing functionalities. Future work will focus on refining the architecture of manufacturing skills and expanding the scope of IPW applications.

Keywords: In-process workpiece; feasibility check; skill-based machining; material removal simulation

1. Introduction

Traditional rigid manufacturing setups often cannot meet the requirements of an increasing number of variants and individualized products, or can only do so at great expense. This has led to the development of skill-based approaches, which offer a high degree of flexibility by allowing production processes to be easily reconfigured and adapted to new requirements, as demonstrated by Dorofeev and Wenger [1]. Capabilities are used to compare requirements of the

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product with capabilities of the available machines and to generate suitable technology chains and production plans. To check the feasibility in detail, the individual skills are simulated and checked for feasibility. To ensure that these simulations are reliable and realistic, and to guarantee error-free execution, each production skill of the machine must have the exact actual state of the product as an input variable. It is not enough to specify the shape of the blank and its dimensions in the form of a bounding box, as previously described by Volkmann et al. [2], as this is too imprecise both for the clamping of the workpiece and for the trajectory planning. For this, 3D models must be available that reflect the actual state of the part. This also means that the 3D model of the part must first be used in the simulation (i.e., in the feasibility check). It must then be passed from skill to skill and further processed during machining. In conventional manufacturing processes, these 3D models are usually referred to as in-process workpieces (IPWs). This paper shows how the concept of such IPWs can be transferred to the methods of skill-based manufacturing and how an Asset Administration Shell (AAS) can be used for storing and exchanging these product data. It presents a concept, explains the advantages of using IPWs in a skill- and AAS-based context, and gives an example of the implementation of the concept.

2. Related Work

The work presented is essentially based on the concepts of skill-based manufacturing and the associated concepts such as the use of the AAS and the terminology of the CSS model. In the following, the most important basics of the paper will therefore be presented and explained.

2.1. Capability, Skill and Service (CSS)

The terminology used in this article is based on the CSS model. The CSS model, which itself is based on the Product-Process-Resource (PPR) model, describes the difference between capabilities, skills, and services. Capabilities are defined as ”an implementation-independent specification of a function in industrial production to achieve an effect in the physical or virtual world”. They therefore describe the capabilities of machines in an abstract way. This also means that they are not executable or callable. There are two types of capabilities: *offered capabilities*, which describe the capabilities of a machine, and *required capabilities*, which describe the requirements of a product to be manufactured. By comparing these two capabilities, known as capability matching, the appropriate manufacturing capabilities for a product can be found. [3, 4]

When it comes to execution, these capabilities must be implemented and controlled on the machine. These implemented automation functions are called skills. More specifically, a skill is defined as ”an executable implementation of an encapsulated (automation) function specified by a capability”. The so-called service describes a capability on a higher level, e.g. within a data room, and contains, in contrast to the capability, also contractual and commercial aspects. However, the service is not relevant for this article. [3, 4]

The CSS model is mainly used in the area of production, as Fay and Neidig [5] show. Especially for the area of automotive production, Grimm et al. [6] show that the CSS model can also be applied usefully and profitably here in order to dynamically assign tasks to resources. Further, Blumhofer et al. [7] show that the CSS model can also bring improvements in the area of intralogistics.

2.2. Skill-based production and skill-based machining

Skill-based production refers to a paradigm in which production machines are designed and built modularly with skills, i.e. automation functions, and can therefore be controlled flexibly. The fact that processes can be designed more flexibly as a result was evaluated by Dorofeev and Wenger [1]. Skill-based machining is a specialized subset of skill-based production that applies this paradigm specifically to the machining field. Machine tools are equipped with skills and can therefore be controlled more flexibly. Within a skill, machine tools are required to perform multiple tasks, make decisions, and simulate [8].

As described in Olbort et al. [9], a skill consists of a skill interface (often OPC UA, see Froschauer et al. [10]) and maps the behavior of a state machine [11]. As soon as the skills reach a certain level of complexity, they must be equipped with a feasibility check in order to be able to carry out the feasibility check. With this feasibility check, production orders can be better planned, as predictions about the duration and energy expenditure are also available [12]. Nguyen et al. [13] show a comprehensive approach of how a detailed feasibility check can be implemented with the help of several different digital twins. On the one hand they use digital twins in the form of AASs, on the other hand in the form of physics-based 3D simulations. They demonstrate this using a work cell with robotic arms and an assembly line.

2.3. AAS

The AAS is a digital representation of an asset of any type, such as a machine, sensor, or workpiece [14]. Its unified metamodel allows data to be stored in a standardized form. An AAS consists of different submodels that provide a standardized data format for a specific purpose, such as a bill of materials, a product's carbon footprint, a description of capabilities or a production plan and production logs. [15]

AAS is one of the main technologies on the path to interoperability in the sense of Industry 4.0. In the literature, the AAS is used to achieve interoperability in a wide variety of applications. Plociennik et al [16] use the AAS as a Digital Lifecycle Passport for the Circular Economy. Among other things, this implementation of the AAS contains data for identifying the product, the properties of the material and lifecycle data. Jungbluth et al. [17] use the AAS to have the corresponding production plans interoperably for different products. They also use submodels for skills and capabilities to implement dynamic replanning of production. The AAS can also be used for interoperability in the context of shared production or marketplace-based production, as Simon et al. and Volkmann et al. [18, 19] show. Standardized submodels for bidding and negotiation enable interoperability across factories and suppliers, so that new supply chains can be created dynamically.

2.4. Different states of the workpiece according to DIN 8580

Among other things, the norm DIN 8580 [20] defines the basic terms needed to describe manufacturing processes. The terms for the different forms of the workpiece during the manufacturing process are also highlighted. Four different forms are distinguished: The shape that is the starting point for each process is called the *initial shape*. The shape that exists at any moment during the operation is called the *instantaneous shape*. The shape at the end of a machining operation is called the *final shape*. If a workpiece is subjected to a continuous series of operations, the final shapes of the individual operations, which are also the initial shapes of the next operations, are called *intermediate shapes*. When a shape is not changed by any operation, it is called the final shape.

In the context of this contribution, an operation can be equated with a capability. This means that the workpiece is in an intermediate shape between the executions of the individual skills. If the part is also tracked during the process, this is the instantaneous shape.

2.5. IPW

The term IPW is used primarily in the context of CAM-based manufacturing to describe the digital 3D model of the instantaneous shape of the workpiece. In CAM-based manufacturing, the milling process is simulated and a material removal simulation is carried out. The geometry of the tool is subtracted from the current state of the workpiece along the tool path to get the IPW [21] . This means that the instantaneous shape of the workpiece can always be mapped and subsequent machining processes have the correct 3D model available as an initial shape. The designation of the virtual workpiece goes one step further and represents a digital image not only of the shape, but also of other properties of the workpiece, such as surface quality, temperature, etc. IPWs and virtual workpieces can be implemented using various technologies, such as Z-map, dexel, voxel and others. [22]

3. Concept for chaining machining skills

In order to better integrate the concept into the overall architecture of skill-based machining, a simplified overview of how skill-based machining can generally take place is first provided (3.2). The basic concept of using IPWs in a skill-based context is then presented (3.3). The simulation during the feasibility check is described first. Section 3.4 then describes the possibilities of this approach during execution.

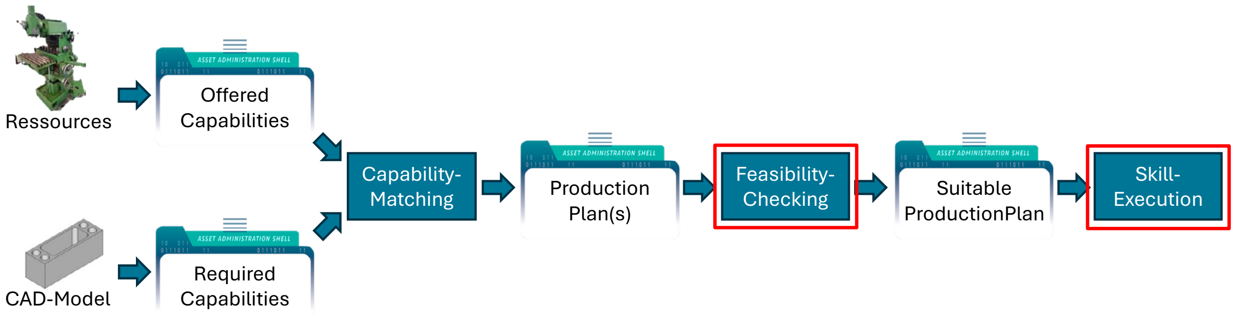

Fig. 1. Simplified overview of the different steps during skill-based machining and the corresponding submodels of the AAS. The steps where this contribution belongs to are marked with a red frame.

3.1. Overview of an AAS- and CSS-based production system

The principle process of skill-based machining can look like this: The production-relevant properties are extracted from a CAD part in the form of features and material properties and stored in standardized form as required capabilities in the product AAS. A matching process is performed with the existing machines, whose functions are again described in a standardized way with the help of offered capabilities in the resource administration shells, so that different technology chains / production processes can be considered. These must then be checked for feasibility, where the main contribution of the use of IPWs plays an important role. Once the technology chain has been checked by the feasibility check, the most suitable production plan is filtered out. When it comes to execution, the results of the feasibility checks are reused and the corresponding skills are executed. The administration shell plays an important role in this concept as an information carrier for the product, where the actual status can be viewed at any time. Fig. 1 shows a very simplified overview. The marked area shows the focus of this work. Accordingly, the concept described in the following section requires at least one production plan, which must be checked for feasibility.

3.2. Checking and Simulating the ProductionPlan using FeasibilityChecks and IPWs

As described in Wagner et al. [23], a ProductionPlan consists of a list of all required skills with their metadata and parameters. During the feasibility check, the execution software connects to the AAS and sequentially retrieves the data for each skill. This means that the end point of the skill, its input parameters, and the type of interface of the skill are queried in the AAS or specifically in the ProductionPlan submodel. The execution software then connects to the corresponding skill on the machine and calls the feasibility check with the appropriate parameters. If an IPW already exists for the part, a link to the IPW is also transferred to the skill with the parameters. The feasibility check then simulates the process and returns the final result data when it is complete. If the skill is a production skill with shape-changing behavior, the skill must return the final shape of the part as an IPW. Conversely, this means that shape-changing skills must be able to perform a removal simulation. This is the only way to pass the current shape of the part as the initial shape to the next skill. Fig. 2 shows the data exchange between the product's AAS, in particular the ProductionPlan and ProductionLog submodels, the execution software and the skill. This data exchange takes place in the same way for each skill, as long that a feasibility check is provided for the skill.

3.3. Interaction with the AAS

As the ProductionPlan contains the parameter set for each skill, it must also contain the IPW or the link to the IPW. To avoid additional parsing of the AAS when creating the ProductionPlan, we recommend storing the current IPW separately in a ProductionLog. This way, the current status can always be viewed and this approach also saves parsing the AAS, which would have to be used to create a reference to the last skill that returned an IPW. By bringing the properties to the ProductionLog, each skill can generically refer to this property. There is a reference to the IPW in the ParameterSet of the skills that require an IPW as input. As soon as a skill is executed and a new IPW is available, this

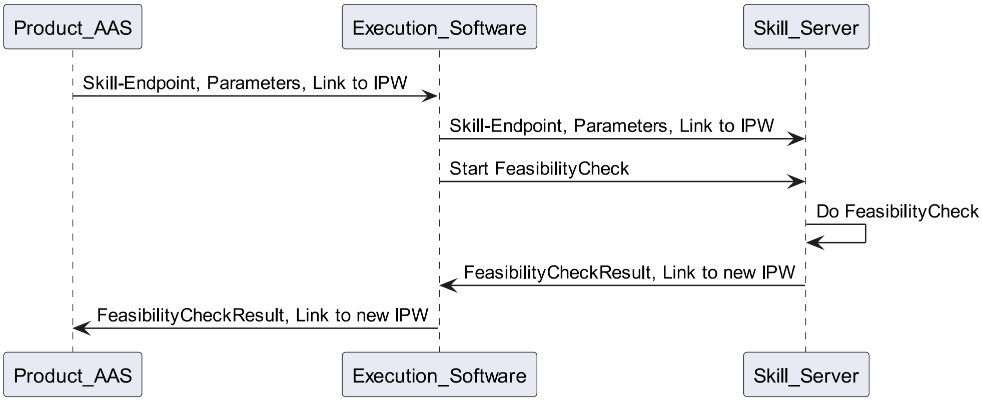

Fig. 2. Data exchange between product AAS, execution software and the skill on the machine. The product aas is passive and only provides an API for reading and writing data.

or its link is saved in the FinalResultData in the ProductionPlan. To ensure that the IPW referenced by the following skills is also updated in the ProductionLog, we recommend working with an "updates" RelationshipElement. The RelationshipElement then refers from the Resulting_IPW in the final result data of the skill to the Actual_IPW in the ProductionLog. This must be interpreted by the execution software so that the Actual_IPW in the ProductionLog is updated. In this way, no references between skills need to be generated individually when creating the ProcutionPlans; instead, the parameter structure or result data structure of the skills can be adopted generically.

3.4. Tracking of the actual state using IPWs

The use of IPWs or process-parallel material removal simulation should also be used during the execution of the skill so that it is known exactly what a part looks like after a skill has been completed and can therefore be passed on to the next skill. There are also benefits in the event of an error. For example, if a skill needs to be aborted, the exact current shape of the part is also available in the digital model. This can be used to complete the part on another machine, for example, or if the part cannot be saved, it can be used as a blank for another part.

4. Prototype Implementation

Fig. 3 shows the implementation of the concept using dummy skills that have an material removal simulation. The test scenario consists of four different machine servers, each with one skill. The first skill performs a raw part cut and is offered by a raw parts warehouse. As no raw part exists before the execution, there is also no input in the form of an IPW. The second skill takes care of the transport and therefore has no output, as it has no effect on the shape of the workpiece. However, the IPW is required as input for the simulation of a gripping process, for example. The third skill is a skill for drilling and accordingly it performs a shape change. To produce four holes, it must be called four times in succession with different parameters. The IPW is updated each time. The subsequent skills follow this pattern.

4.1. AAS and execution software

The administration shell was hosted in a BaSyx repository and can be accessed via REST. The ProductionLog submodel contains a SubmodelElementCollection named 3DInProcessWorkpieceLog, which in turn contains three properties: InitialState, IntermediateState and FinalState based on DIN 8580. The IntermediateState always represents the current state and the two other states are used to store the end and start states of the overall process. As these are properties, only the link to the real 3D model is specified here. The real 3D model is saved directly by the skills in a shared folder.

In the production plan submodel, the list of skills to be called up can be found as a SubmodelElementCollection. Each entry contains the information and properties required to call a skill. The input parameter IPW points to the

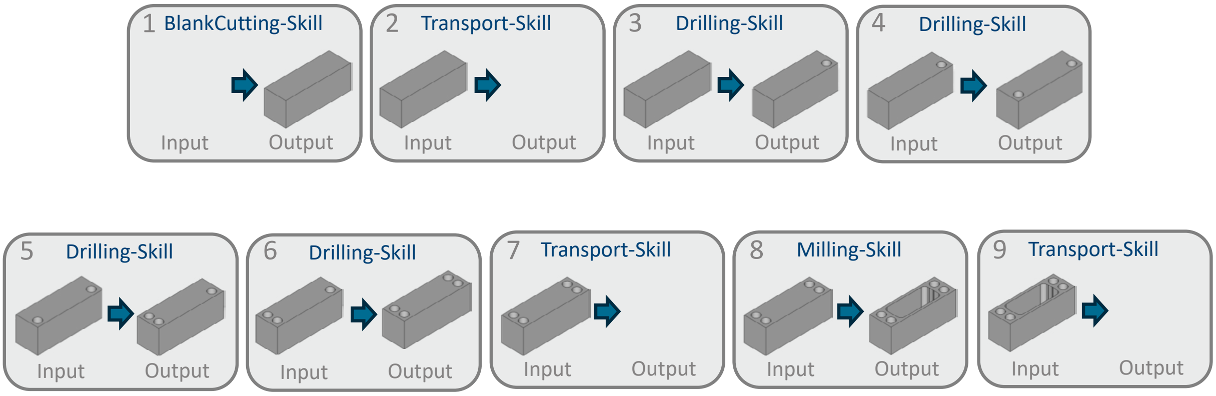

Fig. 3. Implemented Skill-sequence of nine skills. For every skill, the input IPW and output IPW are shown. If the input or output is empty, there is no IPW to transfer.

IntermediateState in the ProdutionLog submodel as a reference. In the FinalResultData, a ResultingIPW property is created if it is a shape-changing skill. In addition, a RelationshipElement is modeled that indicates that the ResultingIPW property updates the IntermediateState property in the ProductionLog accordingly. The update is then performed by the execution software.

The execution software is programmed in Python. A REST library is used to access the administration shell and an OPC UA library is used to access the machine-side OPC UA server and execute the skills on it. The execution software can also interpret relationship elements and resolve references.

4.2. Skill-Server and material removal simulation

The skill servers are also a Python application. The behavior of the skills was programmed in such a way that a fictitious axis setpoint generator generates position data when the skills are called or when the feasibility checks of the skills are called. The material removal simulation in the skill is built using FreeCAD and can be integrated into the skill server. It can be used both with and without a GUI. The material removal simulation is encapsulated via an interface and can therefore be easily accessed. When started, the corresponding IPW, which was transferred as a link via the skill's parameter set, is loaded from the shared folder into the simulation and the material removal simulation follows the position data of the setpoint generator. The tool type and tool diameter are also taken into account. Once the simulation is complete, the simulated workpiece is exported and uploaded to the shared folder. The link to this workpiece is returned via the FinalResultData of the skill.

5. Discussion

The material removal simulation was tested with STL, STEP and FreeCAD formats, with FreeCAD closely followed by STEP showing the best performance. However, the material removal simulation is to be considered purely prototypical at this point and not optimized for performance. The primary focus of this work was to develop and validate a method for exchanging IPWs between machining skills and how the current status of the workpiece can also be recorded in the AAS.

The prototype implementation showed that it is possible in principle to chain skills together in this way. However, it is still to be determined whether the IPW alone, in addition to the geometric parameters of the skill, is sufficient for a comprehensive simulation. This is because the simulation of the skill should also reveal if, for example, a tool penetrates too deeply into the workpiece and thus damages the finished part. This is not possible with the current setup; for example, the finished part would also have to be transferred as a 3D model as input. Furthermore, it must be evaluated whether this will then be part of the material removal simulation or part of the collision simulation of the kinematics of the machine tool.

6. Conclusion and Future Work

Until now, only the bounding box was transferred as information for the initial state of the workpiece for execution and feasibility checking of machining skills. However, since an exact 3D model must be available to successfully plan, simulate and execute manufacturing skills, this article shows how such a 3D model (IPW) can be transferred from skill to skill using the AAS. The states before and after each skill can thus be recorded in the AAS and the initial state is available as an input variable for each skill. The approach described is independent of the IPW technology used and can also be transferred to other simulation mechanisms where models and data have to be exchanged across skills. Even if the prototype implementation was realized without any performance requirements, it still shows the general feasibility of this approach. It remains to be investigated up to which feedrates and simulation speeds a material removal simulation like this can be implemented within a skill and how exactly collision simulations between tool and finished part geometry should be implemented.

Future work will be focused to this topic as well as to the overall architecture of manufacturing skills, as increasing intelligence is required within such complex manufacturing skills. Questions regarding collision simulation, trajectory planning, tool selection and others need to be clarified in order to enable a reliable skill-based machine tool. Overall, this contribution shows a small but important part of the requirements and architecture of skill-based machine tools.

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