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From 3D product data to hybrid assembly workplace generation using the AutomationML exchange file format

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Abstract

The derivation of product features and assembly process characteristics from CAD data is typically manually performed by experienced design engineers. This paper presents an approach for systematic feature detection from CAD data with identification of a product liaison matrix and the corresponding assembly sequence. The results are stored in AutomationML exchange file format to be used in the subsequent step of automatic workplace design based on the idea of optimized resource to process allocation by heuristic search. The approach is demonstrated and validated using an application example of three different lot size scenarios.

Keywords: Computer Aided Assembly Planning; Feature Recognition, Heuristic Optimization, Hybrid Assembly System;

1. Introduction

Changing paradigms in manufacturing driven by market demands require new approaches for versatile and flexible assembly [1]. The traditional approach of manually customizing production cells and setups to predefined products and product families cannot keep pace with the fast changing market developments concerning product demands and technologies, shifts in sales markets and shortened product life cycles [2]. The widespread, conventional tailored production system approach usually performs at one ideal point of operation. Changes and deviations to the ideal scenario usually imply financial losses [3]. Predefined flexibility corridors within the production system based on forecast scenarios can be one option to flexible production, but do inquire financial efforts with uncertain return on invest.

The reconfiguration, reuse and fast ramp-up of modular resources to production cells is considered to be one option to encounter the increased demands of production companies for flexible and changeable manufacturing [4]. Production scenarios are temporarily customized and built up fast for one desired application. Therefore, they always perform in their "sweet spot" of optimized productivity.

Permanently reconfiguring the production scenario and setup does require increased expenses in production planning and design of workplace solutions. A characteristic assembly automation layout runs for several years after it is designed and put into operation. Manual design efforts and time expenses of multiple weeks and months are invested in the draft and setup of a valid and economically feasible production system. For a production scenario in constant reconfiguration, these efforts will exceed the possible productive time of the assembly layout.

Considering possible manufacturing technologies enabling highly flexible and reconfigurable assembly scenarios within a set of constrained production resources in high wage countries, human robot collaboration can be considered to be one key enabler for future versatile production [5]. A survey by Fraunhofer IAO revealed that the collaboration potential is so far not used by manufacturing companies [6] as the absolute number of implemented collaborative assembly workplaces is

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still low. Possible reasons might be derived by the missing background for hybrid assembly workplace planning.

This paper considers one approach to design optimized hybrid assembly workplaces directly from CAD data to abstract assembly workplaces in product, process and resource (PPR) representation. A constant data processing and storage is performed using the AutomationML exchange file format.

2. State of the art

2.1. Generation of assembly liaisons

To generate assembly liaisons from 3D models, assembly features are necessary. Assembly features describe the relation of components in an assembly group and can be defined as „features with significance for assembly processes" [7]. To describe assembly relations like joining entities, constraints and joining methods, joining features are necessary [8,9].

Assembly features are so-called high-level features generated from low-level features. Low-level features are basic geometrical and topological entities, which combination results in form features [10]. Form features represent holes, slots, notches etc. In order to receive high-level features out of low-level features, it is essential to specify two form features of different components and a specific application, e.g. an assembly attribute [8,10]. A generic example of an assembly feature is a cylinder shaped thread in part 1, which is concentric to a punched hole in part 2.

To export features from virtual 3D models, two different approaches have to be distinguished. The external approach is based on neutral geometry data formats like XML, STEP or IGES [11] which leads to a support by most of the 3D CAD systems [12]. However, by conversion from the original format to the neutral format, losses are expected [11]. On top, neutral formats are not able to represent high-level features in the model. Consequently, it is mandatory to create all assembly features from low-level features in an elaborative search.

To obtain the required high-level assembly features, the focus of this work is set on the internal approach. The internal approach recognizes features inside the proprietary CAD engine [11] based on the available API (application programmable interface) of the specific software environment. In this way, the assembly features, originally designed by the design engineer, can be directly accessed.

Unfortunately, this approach still requires to search for low-level features and combine them to assembly features, as the available assembly features do not cope all types of liaisons within an assembly group. The thus required search algorithm can be compared to the complex algorithm from external approach. Based on the direct access to the design features in the software engine, it is considered to be less complex and time-consuming. One major drawback of the internal approach can be determined to be the dependency on the proprietary CAD system.

2.2. Generation of assembly sequences

After the identification of assembly features and generation of assembly liaisons from 3D models, all relations between the product parts are known [13]. Based on the assembly liaisons, assembly sequences can be generated. Unfortunately, the ratio of existing assembly sequences to the number of components is increasing exponentially with every additional part within an assembly group [14,15]. Including the circumstance that most of these *n!* theoretically possible assembly sequences are not technically feasible. A methodology is required which filters unfeasible assembly sequences.

A common approach to determine feasible assembly sequences is to "virtually shake them out" of the assembly group. This so-called collision analysis is based on the principle of "assembly by disassembly" [16]. The logic behind this principle is that the sequence in which a product is disassembled can be reversed for the product to be assembled. Based on this procedure, different assembly sequences can be generated automatically by virtual disassembly. The decomposition can be performed by collision analysis, which disassembles the virtual assembly group by shaking the single components out of the assembly [17]. The main disadvantage of this approach is the high computing power and model preparation time, even for small assembly groups [18].

Another approach uses assembly graphs [19]. The assembly graph represents all components inside an assembly group as nodes and links them only if they are in touch with each other. This concept is based on the strategy to generate assembly sequences by picking components, which are mutually in touch and conclude in a smaller number of unfeasible assembly sequences.

2.3. Hybrid assembly systems

Assembly setups consisting of human operators and robots in temporal and local coexistence and collaboration are called hybrid assembly systems. They can be considered to be one key enabler for reconfigurability [5] and agility during assembly scenario setup, implementation and operation [20]. The goal is to combine the strengths of humans concerning fast adaptability, dexterity and flexibility with the robots advantages of stamina, force and precision [21].

Human-robot-collaboration enables a smooth ramp-up curve of automation without an abrupt increase of investment [22] because technically challenging assembly tasks can be primarily kept to the human operator. The hybrid assembly scenario is a constant morphing setup, which grows with the outer requirements, demands and constraints and can be appropriately adapted to the actual demands [20]. Hence, the choice of feasible collaboration an interaction scenarios between human worker and collaborative robot, to match an accurate selection and allocation of resources to tasks for the current production constraints, is a challenging task in production planning and scheduling.

The procedure of automatically generating different workplace scenarios for hybrid assembly is content of multiple research papers using various approaches to optimize the workload sharing and interaction scenarios [23–25]. The author's earlier papers already address these research topics through integrated resource planning and task allocations in hybrid assembly systems [26], as well as the heuristic optimization of workplace generation during optimization [27].

2.4. Conclusions from the state of the art

The challenge in designing hybrid assembly systems is the beneficial commitment of resources per assembly task, which is strongly interacting with the considered product data, workplace environment, collaboration scenario, defined market demands and constraints. A strong conjunction and interaction between the described product and workplace domains is therefore necessary.

So far, the workplace design process is primarily performed by manual decisions and support of an inhomogeneous software environment. Lohse already described the need for methods and tools to fast configure and reconfigure assembly systems driven by changing requirements [28].

This paper will outline one combined approach of automatically deriving product and process features from CAD data, the identification of assembly liaisons and feasible assembly sequences and the automatic allocation of resources to process tasks and operations. Based on a heuristic search the hybrid assembly scenario is optimized. The different optimization criteria focus on cost, cycle time and technical feasibility of the applied resources.

AutomationML is selected to represent the data storage and exchange format between the different stages of workplace design, assuming that the workplace design results in AutomationML can be directly applied to subsequent processes in a digital design toolchain.

3. Implementation

3.1. Data extraction from 3D models

The described actions are based on an internal approach. To extract all relevant information, the SolidWorks API is used. The API works best with models defined in SolidWorks engine itself. The system searches for three different kinds of assembly features: coincidence, concentricity and threads.

After identifying each single component in an assembly group, the algorithm searches for planar surfaces, radii and helixes per part. The third step examines matches between different parts of an assembly group. Based on the type of match, an assembly feature is derived and allocated to a pair of components, denoted in a numerical manner.

Table 1. Matrix with identified classification of assembly features.

Components	BlankSheet1-1	BlankSheet2-1	Screw M8x30-4	Screw M8x30-1	Screw M8x30-2	Screw M8x30-3
BlankSheet1-1	X	1	5	5	5	5
BlankSheet2-1	1	X	3	3	3	3
Screw M8x30-4	5	3	X	0	0	0
Screw M8x30-1	5	3	0	X	0	0
Screw M8x30-2	5	3	0	0	X	0
Screw M8x30-3	5	3	0	0	0	X

If two components share coincident surface planes, a contact feature is identified, illustrated by black links. In case two components share the same axis of a cylinder or circle with different directions (negative direction is a hole; positive direction is a cylinder) a concentric feature is identified and denoted by a blue link. If two components have a contact feature and a concentric feature in common, they are denoted by an orange link. If two components show coincident threads, a thread feature (grey link) is identified. Table 1 displays an automatically generated liaison matrix including the differently named assembly features and Fig. 1 the corresponding, associated advanced assembly graph.

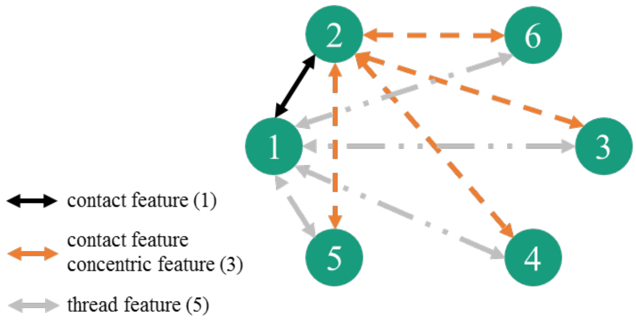

Fig. 1. Associated advanced assembly graph.

Beside the identification of assembly features and liaisons, additional product data is extracted. The information includes the component material, the dimensions of the bounding box cocooning the single product part, as well as the product part weight.

Missing information, such as the fastening torque of the screws or the delivery state of parts (sorted, bulked, stacked) which are not directly stored in the CAD model itself, but relevant for the subsequent resource allocation, have to be added manually by the design engineer.

Table 2. Generated product data derived from CAD model.

Component	No.	Material	Mass [g]	DimX [mm]	DimY [mm]	DimZ [mm]
BlankSheet1	1	1060_Al	601.6	100	150	15
BlankSheet2	2	1060_Al	263.2	100	100	10
Screw M8x30-1	3	Steel	16.92	13	13	36
Screw M8x30-2	4	Steel	16.92	13	13	36
Screw M8x30-3	5	Steel	16.92	13	13	36
Screw M8x30-4	6	Steel	16.92	13	13	36

3.2. Generation of Assembly Sequences

Based on the matrix (Table 1) and the advanced assembly graph (Fig. 1), a feasible assembly sequence can be generated. For this purpose, a proper rule-based system is applied. The rules are defined as follows:

- Mechanical stability has to be guaranteed during the whole assembly
- If an assembled part is not self-retaining or locking, a temporary fixation is necessary

- If two parts need to be joined, all joining elements have to be set at once
- Before two parts get fixed, all components locally in-between these two parts have to be assembled first

The process starts with the selection of the starting component. This component will be the base part to which every additional component will be added. The subsequent components will be selected by their assembly features (represented by the number in the liaison matrix, Table 1) and the assembly rules.

The arrows between the nodes represent the corresponding assembly features, while the green circles represent different components. The starting component of the assembly group is *BlankSheet1*, component 1. The subsequent component to be assembled is selected by the assembly feature with the highest number, which does not interfere with assembly rules (*Blanksheet2*, component 2). Component 1 and 2 are only linked by one contact feature. Therefore the assembly is not stable and has to be fixed during the following steps.

Component 6 (*Screw_M8x30_4*) is added to the assembly as second assembly step. As the blank sheets are fixed with four screws, all screws have to be inserted the same time (steps 2-5), followed by the fastening of the screws (steps 6-9). The final assembly sequence based on described base part can be determined to: 1>2>6>3>4>5. Fig. 2 illustrates the associated advanced assembly graph and the corresponding process steps with ascending numbers.

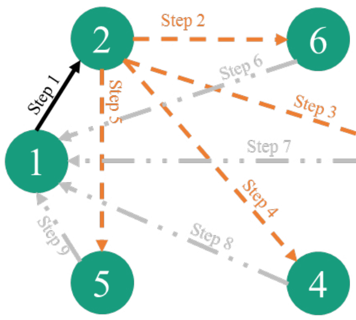

Fig. 2. Assembly Graph of the final assembly sequence.

This procedure can be repeated for every part. In this way, every base part leads to a single assembly sequence and the number of generated assembly sequences is reduced from 720 (6!) to 6. However, not every component suits to be the base part of the assembly group – e.g. there is no reason for selecting a joining element as base part.

Based on the information of the advanced assembly graph for final sequence, the necessary assembly tasks and assembly operation requirements can be automatically derived. Each part has to be separated in the correct amount from its state of supply and handled to the assembly location. Both blank sheets are not self-locking and need to be fixed and positioned during assembly. The joining elements require a joining process for fastening and fixation and the finished product requires a handling operation to finished good supply after assembly.

3.3. Resource allocation and workplace generation

Feasible resources are identified based on their component description in a resource information model in Open Web Language (OWL). The resource information model contains different robot models and robotic tools, alongside auxiliary automation hardware.

In case of a handling device, such as a robot, the dataset contains semantic information about e.g. the reach, payload, repeatability, footprint, degrees of freedom, mass, possible assembly capabilities or power consumption. The available datasets depend on each single hardware class and hardware type. The OWL representation model allows to inherit, extend or adapt the semantic description for each component.

The assembly capabilities provided by single resources within a resource database are compared to the assembly task operation requirements of the present process domain. Operation requirements can be directly fulfilled by single resources or in combination of two resources like handling (*grip, release*) and manipulation (*reach, move*) during a pick and place application. The query for suitable resources is enriched by additional product features, such as required gripper *stroke* or the appropriate range of *torque* for tightening the screws based on the product and assembly group information.

The so-called product-process-resource-triples (PPR) [29] are determined to be a set of appropriate and feasible resources suited for the assembly operations and the underlying product requirements. A linked chain of one technical feasible PPR-triple per assembly task can be considered to be an assembly system.

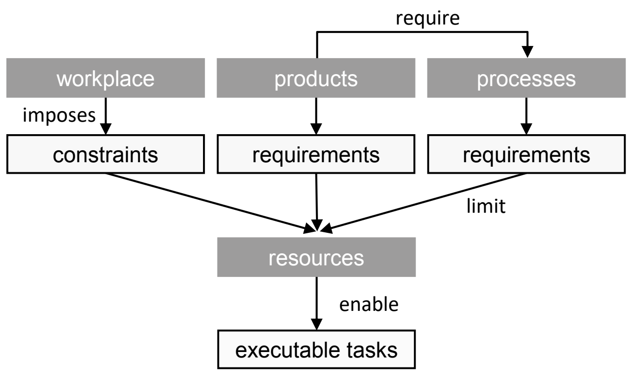

Fig. 3. Procedure to create feasible PPR-triple based on product, process and workplace domain information.

Every linked chain of PPR-triples has its own characteristics and attributes. These characteristics can be compared against the workplace constraints and can be used to optimize the PPR-triples for optimized assembly systems. Possible optimization criteria are identified to be the achievable cycle time, the assembly cost per unit, the technical feasibility of the used resources matching the product and process requirements or the operator steadiness during the interaction of human and robot in hybrid assembly (see [27]).

3.4. Data storage and exchange

The AutomationML exchange data format is an extensible data format in XML notation. The benefit of AutomationML lies in its popularity, wide acceptance and support of different manufacturing companies and component suppliers. Beside its hierarchical topology, it offers interfaces to logic, geometry and kinematic descriptions which can be linked to PLM data or external software tools.

In addition, AutomationML supports the application of reusable roles and interfaces [30] enabling to instantiate meta-model roles and interfaces for requirement, service and capability definition for specific applications[31].

The authors extend the product, process and resource domain representation (PPR) by a fourth domain of general workplace constraints, defining boundaries and general assumptions of the design engineer's goals.

Every PPR domain is represented as one *InternalElement* within the AutomationML *InstanceHierarchy*. Correlations between assembly products and parts, as well as resources and processes can be linked relationally using *ExternalInterfaces* and *InternalLinks*.

All product and assembly group related data derived from the SolidWorks API, such as the single product shapes, dimensions and materials is semantically stored into the product domain. A hierarchical decomposition of the assembly group alongside each single product part *Role* is filed accordingly.

The process data domain contains the process task requirements for matching possible resources, the assembly sequence predecessors based on the derived liaison matrix and the Fraunhofer automation capability score [32] to evaluate the technical feasibility of a process to be automated. The automation capability score describes whether a process task can be performed by operator, robot or both. The score supports the query for reasonable resources from the database.

During the resource allocation process, the so-far missing resource domain is completed by an optimized set of resources matching the workplace constraints, as well as product and process domain requirements. An instance of each resource per PPR-triple and task is created and linked to the corresponding assembly tasks and operations.

3.5. Unit cost calculation

The assembly unit cost calculation bases on a resource leasing model to compare different variable costs instead of the traditional return on invest (ROI). The traditional long-term ROI calculation per assembly use-case and product lifecycle is unable to cope with the paradigm of fast changing and volatile markets and should be neglected as it penalizes assembly scenarios with additional automation hardware.

Only the net time a resource is used in production is calculated at the unit cost. Therefore, the costs in €/s per resource are estimated based on customary purchasing prices. The annual salary per skilled worker is set to 75.000€.

The economical consideration follows the approach of Lotter with a depreciation period of 4 years [33]. The costs for commission and implementation are divided equally to every piece of the required lot size based on rough assumptions for the training and implementation of human and robot.

4. Validation

An assembly group of two solid metal parts and four screws is used as validation example. The derived advanced assembly graph is illustrated in Fig. 2. A total number of nine assembly tasks are identified for this assembly (2^{nd} column, Table 3).

Table 3 describes different hybrid workplace results for three lot sizes and their corresponding optimized resource allocation. It displays the corresponding fitness values of the overall optimization and cycle times per unit, as well as the assembly unit costs. The considered criteria and weights for assembly system optimization are kept to be the same like the ones in [27]. All optimizations are performed using the multi-crossover heuristic approach.

The displayed assembly scenario results show a complete manual scenario for small lot sizes with extended cycle times due to the sequential processing of all assembly tasks by one single human operator. For larger lot sizes, the time consuming handling of screws is automated and performed in parallel to the human operator. This leads to shorter cycle times and lower unit costs per assembly as the fixed costs for implementation and training are divided to more assembly units.

Table 3. Hybrid assembly scenarios for different lot size scenarios.

	Lot Size [pieces]	100	10.000	1.000.000
Part No.	Scenario	hybrid	hybrid	hybrid
1	Separation	operator	operator	operator
	Handling	operator	operator	operator
2	Separation	operator	operator	operator
	Handling	operator	operator	operator
3-6	Separation	bowl feeder (MAFU typ 450 BC lang)	bowl feeder (DEPRAG 11011-2.5)	bowl feeder (DEPRAG 11011-2.5)
	Handling	operator	cobot (UR5) + gripper (SCHUNK KGG 60-40)	cobot (UR3) + gripper (SCHUNK KGG 70-24)
Assembly Group	Positioning	operator	operator	operator
	Joining	operator + screw driver (KOLVER Pluto 10D/N)	operator + screw driver (KOLVER Pluto 10D/N)	operator + screw driver (KOLVER Pluto 10D/N)
	Handling	operator	operator	operator
Overall Fitness		0.259	0.214	0.211
Unit Cost [€]		1.32	0.44	0.39
Cycle Time [s]		32.242	23.933	23.933

5. Conclusion and future prospect

The described approach offers the possibility to support the design engineer's work during the initial step of finding appropriate resource allocations for hybrid assembly scenarios. The approach addresses the need for constant reconfiguration in production systems to encounter the fast changing requirements and constraints from volatile market demands.

By the use of AutomationML data exchange, OWL information models and rule based assignment of liaisons and resources throughout the workplace design steps of product and assembly process analysis, the definition of the assembly sequence and the generation of feasible assembly setups, the overall process gets faster and independent of the design engineers' implicit knowledge and experience.

The created assembly systems of linked PPR-triples can be used in subsequent assembly system design stages to define interfaces, to optimize the layout, to purchase components and to perform the mandatory risk assessment of hybrid assembly systems.

The described automatic exploration of possible resource setups and schedules possibly opens new workplace design solutions, so far not in focus of manual design engineers. It facilitates the comparison of different performance measures to create optimized solutions in short time. The authors will try to extend this approach to one click assembly setup and layout generation, directly from CAD model and PLM data to implement a fully digital assembly workplace planning toolchain for design engineers.

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