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Integrated constraint- and geometric reasoning-based CAPP approach to mechanical assembly planning

PhD-thesis booklet

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1 Introduction

The ultimate goal of mechanical assembly (as an activity) is putting parts together to form a final product which delivers the desired functionalities. However, it is more than just a standalone activity as it also bounds together the upstream results of product design, manufacturing and logistics [13]. Moreover, with the ever increasing need for customer specific products, assembly–through mass customization–also provides a cost efficient solution for achieving the required product variety and thus satisfying customer demands [15]. This central role of assembly in modern production puts the design, configuration and operation of assembly production systems into the focus of numerous researches.

Assembly planning in itself contains various subproblems, nevertheless in the setting of a single workcell the scope of the problem is traditionally limited to Assembly Sequence Planning (ASP) and Assembly Path Planning (APP). These, however, only partially cover the challenges which a process engineer is expected to face along planning phases of workcell design and configuration. Questions such as the process-oriented interpretation of the product design during the specification of a problem; the formulation of constraints on technological, geometrical and physical feasibility; the comprehensible presentation of the resulting assembly plan are all inherently tied to assembly planning. In order to solve these problems plenty of tools and specific representation exists, which are usually aimed at solving a single problem. Without a common (standard) representation and workflow, however, these solutions are separated, even though they are bound together by their objectives in general and are part of the same larger problem.

Hence, the key motivation of the thesis stems from this fragmented nature of the field and the lack of an integrated solution for supporting the complete assembly planning. This poses not only as a matter inconvenience: it also hinders the efficient feedback between the different planning phases and can cause information mismatch between them, i.e., information required at one phase might not be provided from the previous. As probably the most intriguing example the (lack of) integration between assembly sequencing and its geometric validation stands out.

2 Preliminaries

As it is defined in [14], "Assembly Planning is the process of creating a detailed assembly plan to craft a whole product from separate parts by taking into account the final product geometry, available resources to manufacture that product, fixture design, feeder and tool descriptions, etc.".

Traditionally, three main subproblems of assembly process planning are distinguished in the literature, namely: Assembly Line Balancing (ALB), APP and ASP. In addition to their different objectives, the different subproblems are usually separated by the applied representation of the problem as well [14]. In general it can be said, that–even tough there are a number of papers which focus on delivering solutions to one of the subproblems–only a few integrated approaches exist [14, 16, 17].

In the environment of a single workcell, which is in the focus of the thesis, ALB can be assumed to be out of the scope and thus ASP and APP are subjects of investigations. ASP is typically formulated as a combinatorial optimization problem, while for APP solutions are usually produced by reasoning on a detailed geometrical model [18]. ASP is generally considered to be an NP-hard problem and therefore numerous heuristics and soft computing methods have been suggested to solving it, but classic optimization tools are also often applied [17, 20, 21]. Minimizing the changeovers of tools and/or fixtures, the number of assembly directions or the required time for the assembly are very common objective functions of ASP [17, 19].

For solving the ASP problem most approaches apply a graph-based representation of the search space, which is used for reasoning on the possible assembly sequences [18]. AND/OR graphs, precedence graphs are similar representations aim to collect all the required information to the planning algorithm in advance, which can require extensive efforts on preprocessing [20]. Solutions like the Non-Directional Blocking Graph (NDBG) [24] and its later variants succeed in encoding geometrical information, but usually without addressing the elements of the larger setting, i.e., the workcell. Assembly feature-based models offer a decomposition to a detailed micro-level and a combinatorial macro-level planning [22, 23]. These models are able to represent a detailed geometrical model of each assembly step, however the combination of the micro and the macro level is challenging. This is usually also the case for assembly planning methods based on path planning, as path planning is usually a computationally expensive method and its usage during the combinatorial phase has to be limited.

The automation of process planning is incomplete without automated methods for instruction generation [27]. Moreover, due to their increased cognitive load, human workers need enhanced support from the Worker Information System (WIS), in the form of unambiguous instructions delivered using the modality that suits the given environment the best; in addition to classical text instructions, figures, videos, 3D animations, audio instructions, or even Augmented Reality (AR) can be used, too. [25, 26]

After reviewing the current state of the art in assembly planning, the following research gaps were identified:

- There are several popular approaches, but there is no standard or generic representation for CAPP and most of these focus on specific aspects of the problem.

- A direct consequence is that there is no complete, integrated approach for handling the CAPP problem (from geometic models to the work instructions) and the existing solutions operate on separated levels, even though the subproblems are closely related by their nature.

- An illustrative example is the separation of the micro- and the macro-level planning, which often leads to a conflict between optimality and geometrical feasibility. This hinders the effectiveness of both the micro and the macro level.

- Integrated models often assume that every information is available as an input (e.g., in the form of a blocking graph) and therefore there is no room during the planning process for enriching the model with the feedback from a more detailed agent.

- The support for convenient problem instance definition is a crucial point in order to use any CAPP model efficiently. This has to involve the support for generic CAD representations as many of the available solutions are tied to some commercial CAD software.
- Most planning models do not include tools, fixtures or other resources.
- The automatic generation of instructions from assembly sequences is highly desirable, however only a few works consider populating a Worker Information System directly with the results of assembly sequence planning.

3 Problem statement and general assumptions

The thesis presents a framework for providing mixed-initiative decision support for Assembly Planning (AP) of mechanical assemblies. The designated user of such a tool is a human planner working offline, i.e., a process engineer responsible for creating the executable assembly plan for a product.

The scope of the framework is set by the following assumptions:

- The input is a single product, with parts assumed to be rigid without tolerance.
- The assembly operations are executed in a workcell by a single operator.
- The assembly operations are two-handed and monotonous processes and subassemblies are assumed to remain stable.
- For each assembly operation a fixture and a tool is required, which is to be selected from predefined collections.

The three main phases of the proposed framework, which are the following:

1. Problem definition.
2. Plan optimization and validation.
3. Post-processing.

A workflow for the integration of the above three steps is introduced. The input of the problem definition are the geometrical models of the assembly, i.e., it comes from product design. A method is introduced for creating the process planning-oriented interpretation of the product model, based on pairwise analysis of the connections. A *feature-based problem* representation is defined in order to contain this information, along with supporting methods to handle generic Computer Aided Design (CAD) models during the problem definition.

A planning and optimization model is presented, which finds the optimal sequencing of the assembly features, as well as the assignment of tools and fixtures to them. The optimization is performed in a loop which integrates the *macro* and the *micro level* of the assembly planning, thus the result of the combinatorial optimization on the macro level is immediately validated by the detailed evaluation of the micro level and through a feedback the iterative refinement of the problem instance is possible. This reduces the effort required for the problem definition as, opposed to the available macro-level models in the literature, the model does not require the construction of the complete precedence or blocking relationships in advance. On the other hand, this way it can avoid an initially over-constrained problem setting as well.

For the post-processing of the resulting assembly plan an *automated instruction generation* algorithm is introduced, which allows the creation of visual work instructions. To deliver the generated content to the assembly operator, the structure of a suitable digital WIS is presented, which can be automatically populated by the content.

Throughout the thesis the results are discussed separately, according to the above defined phases, but–as they are tightly related by their nature–the main goal of the thesis is the integration, which is also the motivation behind most of the research, design and implementation decisions.

4 New scientific results

4.1 Integrated, hierarchical, iterative workflow for feature-based assembly process planning

In general, solving the assembly planning problem starts at the design specification of the finished product and ends with running production. However, due to the complex nature of the problem, most approaches only address specific aspects of it. Nevertheless, this complexity also fuels a strong need for using computer-aided tools in assembly planning. Positioning the required support, above all, demands the definition of a complete, integrated workflow, which specifies the steps leading from an open, generic geometric representation of the problem to the generation of executable instructions. A key to the success of such workflow is having a suitable underlying representation, which captures the relevant planning knowledge and provides it to the planning phases, thus warranting the feasibility of the plan. The information includes constraints – mostly of geometric nature, but also of technological and economical origin – describing the product, processes and resources in consideration. This includes handling precedence constraints between assembly features, time, resource capabilities (e.g., weight limit and changeover times) and incompatibilities, which is mostly given as an input, but – because of their complexity, especially for precedences – in many cases cannot be completely specified in advance. Coping with the manifold of constraints and the complexity of the planning problem is further hindered by the imperfectness of the input information, requiring the application of traditional engineering principles of hierarchical, iterative, decomposed problem solving. Also, keeping the human in the loop means the essential possibility to involve domain-specific knowledge in any phase of the planning.

Thesis 1. The complete problem of assembly process planning within a workcell, departing from the models of parts and resources, can be solved in an integrated workflow which (1) generates a feature-based model of the problem through pairwise analysis of connecting parts, (2) in an iterative loop combines macro-level planning with geometry-oriented micro-level planning by using constraint feedback, and, finally (3) generates work instructions or executable codes in a post-processing phase.

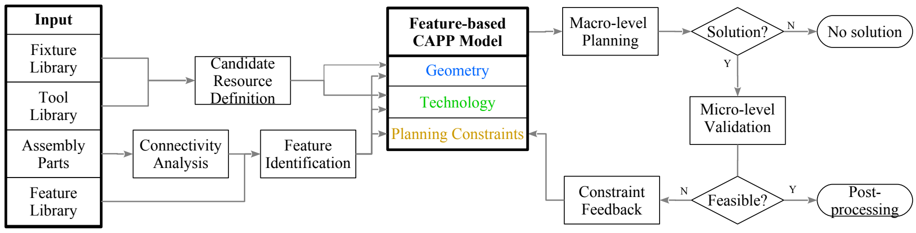

Figure 2: Integrated, iterative planning workflow for planning mechanical assembly of rigid parts.

4.1.1 Application

With the developed assembly feature-based representation, the defined workflow (see. Fig. 2) specifies the role and the interfaces of each step in it, thus allowing the integration of computer-aided planning tools, as well as human input. Most importantly it decomposes the core of the planning problem to the macro and micro level connected by feedbacks in the solution loop, which–in the one hand–enables the iterative improvement of the solution and–on the other hand–also simplifies the required input by allowing the injection of additional constraints. This cautious approach (i.e. starting with a possibly underconstrained model) also helps avoiding the definition of overconstrained and thus unsolvable problems.

A preliminary version of the workflow was first developed and applied in a project[1] for supporting the design and planning of Remote Laser Welding (RLW) workcells. The current version was successfully demonstrated in three different types of real-life assembly planning problems (automotive, plumbing, pneumatics) and the results were utilized in domestic and international research projects.

4.1.2 Related publications

The thesis is based on Chapter 4 of the dissertation and publications [C7, J1, C8, J2, J3]

4.2 Constraint model for macro-level assembly planning

The hierarchical decomposition of the planning workflow defines macro-level assembly planning as a combinatorial problem, where the resulting plan is composed of a sequence of two-handed mechanical assembly tasks of rigid parts, which after the last task brings the parts into their final assembled state. Each task consists of an assembly feature specifying two parts to be assembled and the assigned tool and fixture. The input of the problem are, hence, the sets of features, tools and fixtures. A typical assumption here is that every feature has to be assigned to a task, however, it can be shown that this puts greater burden on the input specification and can create infeasible problems. In most cases the technological interpretation of the product design result in multiple alternative features and manually selecting a subset of them raises the chance of

[1] http://www.rlw-navigator.eu

creating an infeasible input. Thus, the feature selection is expected to be part of the macro-level planning problem, which can be formulated as the selection and sequencing of assembly features and assigning resources from a given set of tools and fixtures to each of them.

An essential requirement on the macro-level planning is the feasibility of the plan, achieved by enforcing technological constraints and those provided by the detailed micro-level validation. This requires the specification of a constraint model of the problem on the macro level. Moreover, the economic aspects of workcell design demand that the resulting process plan satisfies time constraints, therefore a time optimal solution is desired.

Thesis 2. The macro-level assembly planning problem in a feature-based assembly model, which includes the selection and sequencing of two-handed assembly features and the corresponding tool and fixture assignment can be formulated as a constraint program, which (1) minimizes the time required for the assembly, given as the sum of the processing times of the selected features and the time required for the fixture and tool changeovers and (2) enforces the technological and feasibility constraints.

4.2.1 Application

The defined constraint model was implemented using the MiniZinc constraint modelling language as it offers strong expressive power for handling both the complex technological constraints and the ones fed back from the micro-level validation.

The model takes the following input:

- The set of the fixtures and for each fixture a weight limit and a changeover time.
- The set of the tools and for each tool a changeover time.
- The set of two-handed assembly features which specify two parts to be assembled and a process time.
- The set of candidate tools for each feature.
- The set of candidate fixtures for each feature.
- The set of disjunctive constraints on the sequence, tooling and fixturing.

The model minimizes the time required for the assembly, which is the sum of the processing times of the selected features and the time required for the fixture and tool changeovers, such that:

- The resulting assembly plan for K parts has $K-1$ steps and the assembly is complete after the last step.
- Each feature is executed in one of the candidate fixtures, with one of the candidate tools given to that feature.
- At each step the two parts of the feature are attached to the parts assembled to them in the previous steps.

- At each step the part grasped by the feature is either a part specified by the feature or a part attached to it.
- The total weight of the grasped part and the parts attached to it is less than or equal to the weight limit of the fixture.
- The disjunctive constraints are satisfied.

The model is extended in each iteration of the solution loop with the information gained from the micro-level validation and the solution space is restricted step by step to the executable solutions only. With the resource assignment and feature selection and sequencing in the same model, the approach also inherently implements subassembly definition where the assigned fixture determines the features to be realized in one setup.

The constraint model was successfully tested and evaluated on real-life usecases of different problem types, demonstrating the expressive power of the model and also its efficiency as the results were calculated within an acceptable computation time with proven optimality, thus minimizing the sum of the required process and changeover times of the assembly plan.

4.2.2 Related publications

The thesis is based on Chapter 5 of the dissertation and publications [J2, J5].

4.3 Geometric reasoning for micro-level validation of assembly plans

A detailed validation of the macro-level plan is required in order to ensure its feasibility.An applicable approach is to use various expert agents for executing micro-level validation according to various aspects. An agent is expected to provide the result of the validation in the format specified on the macro level as feasibility cuts. One of the most essential aspects is to evaluate the geometrical feasibility of the motions defined by the assembly plan. The sequence of assembly features and the assigned resources define for each step the moved and base components and their locations and movements in forms of transformation, which can be validated by means of collision detection to check if there is a geometrical conflict when executing an assembly task. Using generic mesh models for geometric representation is desirable as it allows easy access to the models and the application of powerful collision check algorithms. However, mesh models are also prone to faulty triangulation and imperfect contacts between them, which hinders the utilization of collision detection. Therefore more advanced algorithms are required to overcome these limitations and still harness the advantages of generic mesh models.

Thesis 3. The micro-level geometric validation of feature-based assembly tasks–which uses the mesh models of the part, fixture and tool geometries–provides feedback for the macro-level planning in the form of generic constraints on the Task-specific Liaison Graph (TLG), which can be generated as the result of combining collision analysis for the local motion and for the approach motion.

4.3.1 Application

During the micro-level validation at each assembly step, the results of the collision analysis are converted into generic constraints by reasoning over the TLG. In the TLG the nodes are the already assembled parts, the applied fixture and the tool. The fixture node is connected to the grasped part and the tool node is connected to the moved part of the task, the edges between the parts are the assembly features directly realized in the previous and in the current assembly steps. Collisions in the validation mean infeasible paths in the TLG, which are used to generate feasibility cuts as feedback for the macro-level planning in the following format: $\{\alpha, \{\beta_1, \ldots, \beta_e\}, \gamma, \delta\}$. Here the preceding feature α is the current feature, the set of succeeding features $\{\beta_1, \ldots, \beta_e\}$ is the set of features possibly causing collision (with the exception of α), whereas the tool γ and the fixture δ are the resources assigned to the current task (only if they take part in the collision). A feasibility cut enforces that in the assembly plan feature α has to be left out *or* it has to precede at least one feature in $\{\beta_1, \ldots, \beta_e\}$ *or* it has to be done with a tool different from γ *or* in a fixture different from δ.

The analysis of the local motion supports handling imperfect mesh models by applying the developed Disassembly Direction Metric (DDM) for evaluating the feasible linear directions of movement between two polygon meshes. This approach assists the problem definition as well, by calculating the linear axis for the direction and the depth value of an insertion assembly feature.

The micro-level validation methods were tested and evaluated in self-generated abstract geometric instances and were successfully put in use in real-life use cases of various problem types. The collision detection based geometric validation of polygon mesh models proved to be effective in generating feasibility cuts for the macro-level plan. The combined application of local motion and approach motion, including path planning was further used as input to instruction generation.

4.3.2 Related publications

The thesis is based on Chapter 6 of the dissertation and publications [C8, J3, C9, C11].

4.4 Automated work instruction generation and delivery

The final step in assembly planning is the execution of the plan, either by human workforce or a robot or by their collaboration. Nevertheless, every operator requires instructions, which are precise and clear representation of the plan and are delivered in a readable format. For human operators, who still dominate the field of mechanical assembly this means easily comprehensible work instructions. Modern worker instruction systems offer the ability to display dynamic multi-modal instructions but providing skill- and context-dependent instructions is also desired as it further increases the flexibility of production.As they are bound closely to the assembly plan, the automated generation of the work instructions is the last step of the presented assembly planning workflow. This requires algorithms which perform the translation between the feature-based assembly plan and the instructions, while also extending them according to the requirements of supporting multi-media interfaces, skill and context-dependency.

Thesis 4. The planning results of a feature-based assembly model can be automatically post-processed (1) into multi-level textual instructions by using templates corresponding to the feature types and to the changeover and pick-up operations and (2) into 3D, interactive, animated work instructions, (3) which can be used to automatically populate the database of a worker instruction system.

4.4.1 Application

The developed algorithms are able to automatically generate human readable instructions from feature-based assembly plan representations. The assembly features serve as a template for actions performed by the human or machine operator in the workcell. Extended with the additional actions, such as tool and fixture changeovers, this supplies a complete description of the assembly actions. A work instruction system for delivering context- and skill-dependent multi-modal work instructions to human workers was designed, implemented and used as a testbed for the human instruction generation. In the real-life demonstrator case of a European research project[2] on symbiotic human-robot collaboration the results were put in use, where instructions for an automotive assembly use-case were generated automatically and were used to populate the implemented work instruction system.

4.4.2 Related publications

The thesis is based on Chapter 8 of the dissertation and publications [C6, C7, O12, C10, C11, J4].

5 Utilization of the results

5.1 SYMBIO-TIC

The SYMBIO-TIC project (introduced in Section 2.6.2. of the thesis) provided multiple opportunity for the application of the research results. First, the automotive use case of the supercharger (presented in Section 7.2 of the thesis) was a demonstrator, supplied by the Volvo Car Company as a partner of the research consortium. The supercharger served as the first test of the implemented assembly planning approach and it provided the content for the instructions.

With the project's focus on the human-robot collaboration, the generation and delivery of human instructions was also very important and thus the project also served as a test ground for the developed automated instruction generation methods. The Human Machine Interface Controller (HMIC) was successfully implemented during the course of the project and it was deployed as a demonstrator at the premises of the University of Skövde, Sweden. The system was integrated with the unit controller and the scheduling cockpit of the workcell and thus completing the *symbiotic ecosystem* defined by the project. The HMIC was also deployed and put in use at the industrial site of an aerospace company in Spain, where it provided the instructions to the flexible assembly operations of aircraft wings.

[2] http://www.symbio-tic.eu

5.2 National research project

Outside the international research projects the results were further developed and put in use in a Hungarian national research project ("Ipar 4.0 kiválósági központ") funded by the GINOP-2.3.2-15-2016-00002 grant. Assembly planning was one of the key research areas of the project and it provided the working example of the ball valve and the pneumatic cylinder as use cases. Both of them were successful subjects of the complete assembly planning workflow and the resulting instructions were used to populate the HMIC system.

The project also aimed building up physical demonstrators in SZTAKI's learning factory laboratories located in Győr and Budapest.These sites also operate as public dissemination locations and the results were demonstrated to the public at multiple occasions with acclaim in events such as the Researcher's Night.

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