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Procedia CIRP 00 (2016) 000–000

www.elsevier.com/locate/procedia

49th CIRP Conference on Manufacturing Systems (CIRP-CMS 2016)

Towards feature-based human-robot assembly process planning

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Abstract

The paper proposes a generic approach to automated human-robot assembly process planning. A novel feature-based model of the assembly process is presented which can be synthesized from the standard CAD model of the product and the description of the applicable resources. As a first step towards automated planning, the paper focuses on generating constraints that ensure plan feasibility, as well as on the formal verification of fully specified plans. Examples are given from the domains of robotic remote laser welding and collaborative human-robot mechanical assembly.

Keywords: Assembly planning; Robot; Feature

1. Introduction

Robots are becoming crucial, more and more indispensable elements of today's production and logistics systems, thanks to their *flexibility*, reliability, and warranted high quality of work. Together with this trend in industrial automation there increases the need for production *efficiency*. Hence the challenges are manifold: the typically conflicting requirements for flexibility and efficiency should be consolidated along with observing all the technological and geometrical constraints that are implied when using robots in a particular application domain. Designing the structure, planning and verifying the behaviour, as well as controlling and monitoring task execution of a robotic system should go hand in hand, in close interaction, facilitated by decision support tools that use generic models of products, robots and other resources (like workcells, workers, fixtures, tools) that take part in actual production.

Our specific domain of interest is *assembly* where robots inhabited mass production environments, e.g., in the automotive industry, for a long time. However, one of our main concerns here is to find a resolution to the flexibility vs. efficiency dilemma in small-scale, even personalized production that calls for new models and methods of automated *assembly planning* [1,2]. Secondly, in robotic assembly one can observe a shift from complete automation towards human-robot collaboration in shared workspaces [3]. Provided safety requirements can be warranted (e.g., by vision-guided active collision avoidance [4]), the scope of potential applications will grow to a large extent. The ultimate *goal* of this research is to develop such automated *process planning* tools and technologies for supporting human-robot assembly that are generic across a number of domains.

Our current research centers around symbiotic acting together of human workers and robots in engine assembly, where operations on mechanical parts (such as placing, insertion, fitting, screwing, etc.) can be performed both by humans or robots. However, the scope includes, as an extreme, also fully robotic assembly like *remote laser welding* (RLW) where welding tasks are accomplished by a laser beam emitted from a scanner that acts as the end-effector of a robot [5–7].

Two general approaches are unanimously taken to cope with the inherent complexity of assembly process planning: (1) *aggregation* that suggests a hierarchical decision scheme separating macro and micro planning [1], and (2) feature-based *decomposition* that helps structuring domain knowledge around local assembly features. *Assembly features* that are derived from the CAD model of the product [8] imply tasks, the use of specific resources, and modes of task execution [2]. While *macro planning* is responsible for (re-)configuring assembly workcells, ordering the tasks and assigning resources, *micro planning* involves motion, path and trajectory planning, generation of work instructions and the determination of process parameters. In robotic assembly micro planning is especially challenging since feasible, collision-free trajectory of the robot has to be generated while striving for minimal cycle time. Nowadays, thanks to advanced digital data acquisition, motion capture and visualization methods, assembly planning is accompanied by virtual evaluation, testing and simulation [8–10]. However, simulation of virtual assembly cannot support completely the planning process [10]. In fact, *geometric reasoning* combined with motion planning should be used for ensuring feasibility of robotic assembly sequences. Furthermore, recognized assembly features can provide the basis also for generating human work instructions.

Automated process planning in general is one of the hardest problems in production engineering because it has to concern both the worlds of design and production. Still, based on our experience in planning in the machining [11,12], sheet metal bending [13] and recently, the RLW [5–7] domains we believe that while process planning requires observing a wide variety of domain specific constraints (on tools, setups, operations and their ordering, movements, etc.), there can be defined an underlying *generic representation* for capturing all the essential elements, relations and criteria of the process planning problem. This paper presents the first steps towards such a generic model in robotic assembly, together with a proposed methodology that handles the *verification* of feature-based robotic assembly plans. Examples from both the human-robot mechanical assembly and the RLW domains will be provided.

2. Problem definition

This paper looks at assembly process planning as part of the workcell configuration problem, as depicted in Fig. 1. The initial steps of this workflow *extract assembly features* from standard CAD product models, and generate one or more *assembly tasks* for each feature. Each task is allocated to a workcell of the assembly system during *workcell allocation* (line balancing). Workcell configuration focuses on designing the layout and the behavior of an individual workcell, given the set of tasks to be executed in it. *Assembly process planning* is responsible for generating the optimal behavior: *sequencing the tasks* and *assigning them to resources* in such a way that a certain performance measure (e.g., the cycle time) is minimized. The computed plans are submitted to motion planning, and work instructions are generated for all resources: program code for robots, and work instruction sheets for human workers.

In the sequel, it is assumed that a task can be executed by a robot, a human worker, or a combination of these two. In addition to the robot or human resources, appropriate tools and fixtures might be assigned to the task as needed.

In order to make a step towards automated assembly planning, this paper proposes a formal model of the assembly process, and presents an approach to the formal verification of the feasibility of assembly process plans from a number of points of view, including technological and geometric feasibility of the process.

3. Feature-based planning approach

During assembly two or more parts or sub-assemblies are joined in order to create a product or a new sub-assembly. Various types of assembly operations are applied in present days' production systems and most of them can be executed both by robots or manually. This section introduces the models of the assembly features in scope, the geometry, the surrounding environment (workcell) and the applied resources.

3.1. Modeling of part geometry

During planning, part geometry will be modeled as triangle meshes. This approach does not utilize the advantages of descriptive CAD representations (e.g., native formats of CAD systems), however triangle meshes are generic and can be used efficiently for proximity queries in collision avoidance [14,15]. In addition, a common limitation on using native CAD formats is that they usually define constraints by using mating pairs and therefore assembly features with more than two components are not captured as one.

Considering rigid, homogeneous parts of a known material, their volume, mass, center of gravity can be calculated by using the mesh model. These physical properties of the part geometry have to be linked to the geometric model.

3.2. Modeling of assembly features

Assembly features implement *kinematic constraints* to join components. In the presented approach only rigid components are considered therefore only features that implement fixed kinematic pairs are in the scope, while gears, belt drives, etc. are excluded. It is assumed that the components to be assembled within a task do not affect its feasibility, i.e., the components are compatible. The approach presented in this paper aims to be generic and extensible, thus besides placing, insertion and screwing, RLW tasks are also modelled. The currently included features are shown in Fig. 2.

Placing and insertion determine the relative position of parts that were earlier independent. These will be referred to as *relative positioning feature types*. Other feature types (e.g., screwing, welding, etc.) create a permanent link between parts with momentarily fixed relative position. These will be named *permanent positioning feature types*. All permanent positioning features must be preceded by the relative positioning features between the parts that they join together.

We also assume that the sequence of tasks describes a monotonous assembly, i.e., there are no disassembly tasks (not even temporarily). Auxiliary tasks, such as put-away, material handling, etc. are ignored here, since these can be generated only after the assignment of assembly tasks to the workcells.

3.3. Modeling of technological parameters

Placing requires the goal position of the component to be placed, which is described by the location and the orientation as a six-dimensional vector ($x, y, z, \alpha, \beta, \gamma \in \mathbb{R}$). The path of the component can be any collision-free path in its first segment until the *near position* defined by safety distance (d) is reached and a translation in the second segment. By using non-zero safety distance sliding of components on each other can be avoided.

Insertion is described with the same parameters as placing, however, the path is decomposed into two segments: the first segment is *placing* the component into a position which allows moving the component into the receiving component along a single axis movement. The reference frame attached to the

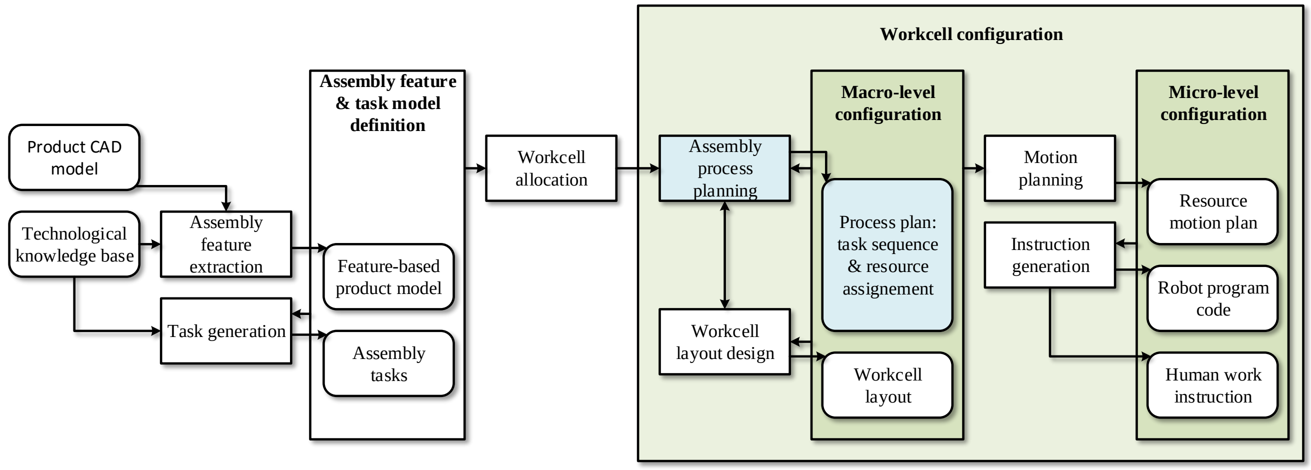

Fig. 1. Assembly process planning and verification in the workflow of workcell configuration. The problems in scope are highlighted with blue.

component is defined so that the second segment of the movement (the actual insertion) is carried out parallel to its z axis. A safety distance d defines a clearance that separates the receiving geometry and the end of the first movement segment (near position).

Screwing is considered as a similar operation to insertion as first the screw has to be moved to a position which allows starting inserting and fastening the screw. The components joined by screwing are placed by preceding relative positioning features. The reference frame attached to the component is defined so that during fastening the screw the tool movement is along its z axis and the operating tool sinks an amount equal to the lead of the screw in each revolution.

RLW differs from traditional welding technologies as there is no direct tool contact required, the heat is delivered by a laser beam emitted from the tool mounted on a robot (therefore, here no manual operation is allowed). Certain technological constraints on the laser beam–specifically, the incidence angle and the minimal and maximal focal length of the beam–determine a truncated cone volume for accessing a stitch, where the axis of this cone is the normal vector of the surface at the center point of the stitch. On the other hand, laser power and laser speed are also specified and determine the tool speed. The technology and its relation to workcell configuration are explained in detail in [5,6].

3.4. Modeling of the resources

Industrial robots are modeled as open kinematic chain mechanisms. Similarly, the *arm of a human worker* can be considered as a 7 Degree of Freedom (DoF) open kinematic chain mechanism ending with a Tool Center Point Frame (TCPF), where the tool is to be held. This implies that the hand of the human worker is not considered and the rest of the body neither. This simplification is based on the assumption that the assembly and the parts to be assembled are small enough to be in interaction only with the human arm. The corresponding geometric models (triangle mesh) of the robot or human arm are attached to the links of the kinematic model which allows collision detection during plan verification.

Tools required for the assembly operations are modeled with their geometry, and a specified mounting point which determines the connection of the tool end to the TCPF of the robot or human arm. The contact points of the tools, where the components and the tool meet, also have to be specified in order to be able to determine the component position and orientation during collision queries.

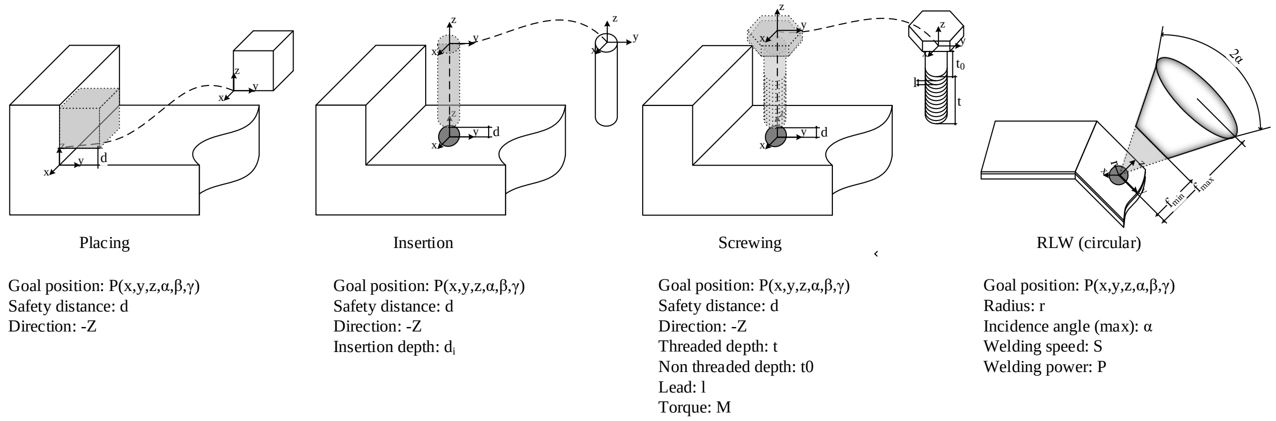

Fig. 2. Examples of assembly feature types.

3.5. Modeling of the workcell

In the presented approach it is assumed that during an assembly process a *new component* or sub-assembly and an already present *base component* or sub-assembly are joined. The base component is held in its place in a *fixture* which determines its position and orientation. Currently the fixture is not modeled in detail, however there are assumptions regarding fixturing. It is assumed that the base component's position is maintained during an assembly task. Therefore, the first task is placing the first component to the position determined by the fixture (i.e., a placing feature with the fixture as a base component). Fixtures are considered to have open and closed states. A closed fixture is able to hold components regardless their stability, while stability check needs to be applied against an opened fixture. It is also assumed that fixturing and assembly is done in one setup, i.e., there are no changeovers and therefore the stability of once assembled components is kept monotonously.

The new component is always picked up from a previously specified location in a given orientation (e.g., from a feeder or from a pallet), which is the *pick-up location*. The completely assembled product is moved to a *put-away location* which means placing the complete assembly to a specified location in a specified orientation.

4. Automated verification of plan feasibility

A key enabler in automated assembly process planning is a collection of models and algorithms that can *verify* and guarantee the *feasibility* of process plans from all relevant points of view. The aspects considered below include technological feasibility, collision avoidance (i.e., geometrical feasibility), and stability. To facilitate a future transition from plan verification to plan synthesis, the algorithms not only classify completely specified plans as feasible or unfeasible, but they also generate *constraints* that ensure feasibility.

The generated constraints refer to the combination of resources, tools, and fixtures that are capable of performing certain assembly tasks and to the ordering of the tasks. In addition to atomic constraints, logical combinations of such constraints (i.e., reified constraint) are also allowed. Consider an example in which a part attached to the workpiece by task $A1$ blocks access to another task $A2$ if $A2$ is executed by a large tool T. Nevertheless, $A2$ may be executed even in this workpiece configuration by some other, thinner or more flexible tool. Such a situation can be discovered by collision detection and can be circumvented by generating the following constraint:

```
"If task A2 is executed using tool T, then
assembly task A2 must precede A1."
```

In the sequel, we present approaches to generate such constraints grouped by the origin of the constraint.

4.1. Technological feasibility

To assess the feasibility of the plan from a *technological* point of view, the plan is verified against a technological knowledge-base defined in a rule-based expert system. The rules declare constraints on the assignment of resources and tools to the tasks, as well as on the feasible orderings of the tasks. The technological rules cover the following main aspects:

```
(defrule AssignPlacingToHuman
"Assignment of placing feature to human"
    (FEATURE_TYPE ?feature placing)
    (PLACING_FEATURE ?feature ?part_fixed ?part_moving ?  ?)
    (RESOURCE_TYPE ?resource human)
    (PART_PROPERTIES ?part_moving ?weight ?)
    (<= ?weight HUMAN_LIFTED_WEIGHT_LIMIT)
    =>
    (assert (CAN_PROCESS ?feature ?resource)))

(defrule AssignPlacingToRobot
"Assignment of placing feature to robot"
    (FEATURE_TYPE ?feature placing)
    (PLACING_FEATURE ?feature ?part_fixed ?part_moving ?  ?)
    (RESOURCE_TYPE ?resource robot)
    (PART_PROPERTIES ?part_moving ?weight ?)
    (LIFTED_WEIGHT_LIMIT ?resource ?weight_limit)
    (<= ?weight ?weight_limit)
    (CAN_BE_MOUNTED ?robot ?end_effector)
    (CAN_GRASP ?part_moving ?end_effector)
    =>
    (assert (CAN_PROCESS ?feature ?resource ?end_effector)))

(defrule PrecedencePlacingScrewing
"Precedence between placing and screwing"
    (FEATURE_TYPE ?feature1 placing)
    (FEATURE_TYPE ?feature2 screwing)
    (PLACING_FEATURE ?feature1 ?part_fixed1 ?part_moving1 ?  ?)
    (or (SCR_FEATURE ?feature2 ?screw2 ?part_fixed1 ?part_moving1 ?  ?)
       (SCR_FEATURE ?feature2 ?screw2 ?part_moving1 ?part_fixed1 ?  ?))
    =>
    (assert (PRECEDES ?feature1 ?feature2))))
```

Fig. 3. Examples of expert rules for robotic and human placing and a screwing operation. The rules also capture the different nature of the resources (e.g., human does not need tool for placing).

- Applicability of the robotic or human resources to execute the given assembly task, including aspects of dexterity, precision, and payload;
- Applicability of the tools to the given tasks, e.g., compatibility of gripper and part in case of placing and insertion features, or compatibility of the screwdrivers and the bolt;
- Compatibility of resources and tools, i.e., whether the robot can be fitted with the given tool or the human can handle the tool;
- Whether the precision required for executing the task can be achieved by the given combination of resources and tools. In case of robotic resources, open-loop controlled robots and robots guided by, e.g., vision systems must be differentiated;
- Precedence conditions between the given assembly tasks;
- Potential application-specific rules.

Some examples of rules are depicted in Fig. 3. The first rule states that a placing task can be assigned to a human worker if the weight of the part moved does not exceed the weight limit specified for humans. Similarly, the placing task can be executed by a robot if it has a gripper compatible with the part moved and the part weight does not exceed the payload of the robot. The final rule states that the parts joined by screwing operation must be first joined temporarily by placing operations.

4.2. Geometrical feasibility

A crucial condition of feasibility for assembly tasks is that they can be executed without any collision, given the workpiece configuration at the beginning of the task, as determined by the given task sequence. The question of collision avoidance is investigated in two parts: (1) whether the core, local movement encoded by the assembly feature can be executed without collision, and (2) if the part and the tool can approach the region of interest on a collision-free path.

To reflect the workflow (see Fig. 1) in which no workcell configuration model is available at the time of task sequencing, and hence, no detailed model of the resources and their relative placement is available, collision detection is performed in the Cartesian coordinate system attached to the workpiece. While this approach precludes the most typical types of collision involving parts and tools, a detailed investigation covering collisions of all resources will be possible in the robot joint configuration space only after workcell configuration.

4.2.1. Geometrical feasibility of the feature

The local feasibility of the assembly feature is defined as the ability to execute the core motion prescribed by the feature, from the near position until the goal position without any collision. Since different feature types prescribe different movement patterns, the detailed geometric models used for collision detection differ by feature type. For insertion and screwing, where the near and the goal positions are completely given in the Cartesian coordinate system, and they are interconnected by a linear movement, part and tool geometries are linearly extruded along the movement. Specifically, the extruded tool geometries are tested for collisions against all parts except for the parts moved by them. The extruded part geometries are tested for collisions against the current workpiece configuration minus the parts included in the feature.

For other technologies where the tool position is not completely defined in the feature, local feasibility of the feature requires the existence of a collision-free tool position and near-to-goal motion. Again, the detailed geometrical model depends on feature type. For instance, for RLW, where the laser beam can be regarded as the tool, the feature is locally feasible if there exist a straight line section (laser beam model) terminating at the welding stitch whose length is between the minimal and maximal focal length and whose inclination angle is in the defined range.

4.2.2. Geometrical feasibility of the approach

In addition to the geometrical feasibility of the feature itself, the collision-free access of the tool must also be ensured. This can be verified by solving a collision-free path planning problem from a remote position (either the pick-up position of the current part, if defined in the workcell model, or from an arbitrary remote position) to the near position in the feature. For solving the path planning problem, an implementation of the rapidly-exploring random tree (RRT) planner [16] and the PQP proximity query package [15] are used.

4.3. Stability

For each relative positioning (placing or insertion) task in the plan, the stability of the actual workpiece configuration must be ensured by the applied restraints. A placing task is considered to be stable if the part is placed into a fixture (or the applied resource holds it as a fixture until the parts are permanently joined), or if the center of gravity of the placed part is above the convex hull of the contact surface. An insertion task is regarded as stable if the z component of the insertion direction in the workcell coordinate system is negative, or if the inserted part is held in a fixture (or by a resource used as a fixture).

5. From plan verification to process planning

The ultimate objective of this research is developing a semi-automated software tool for assembly process planning. Such a tool must not only build *feasible* plans, but plans that perform well according to the defined performance criteria and reflect the intentions of the human planning expert. The multiple criteria considered must include cycle time, investment costs related to the resources used and operational costs, number of changeovers between resources or tools, floor space, as well as ergonomy for human workers. Additionally, the software tool must be able to incorporate any potential user preferences received from the human expert via an intuitive user interface in a mixed-initiative planning procedure.

In addition to the above presented models and algorithms for verifying the feasibility of a single plan, the planning tool must be able to evaluate the performance of the computed plans (and calculate efficiently optimized building blocks for individual tasks, such as shortest collision-free paths for evaluating the cycle time of the corresponding task), as well as to generate alternative plans. Due to the high-dimensional search space, efficient meta-heuristics are required to target search effort to promising alternatives. We consider the above presented results as a first step towards that final objective.

6. Case studies

6.1. Engine assembly by screwing

The first case study investigates the assembly of a car engine supercharger. Since the complete supercharger consists of more than a hundred parts, focus in this simple illustration will be given to the ordering of two assembly tasks involving three sub-assemblies. The first task is the permanent joining of the resonator inlet (lowermost, green sub-assembly in Fig. 4) and the throttle (middle, silver sub-assembly) by three screws, by a human worker using a pneumatic screwdriver. The second task is placing the resonator bottom (topmost sub-assembly) on the throttle.

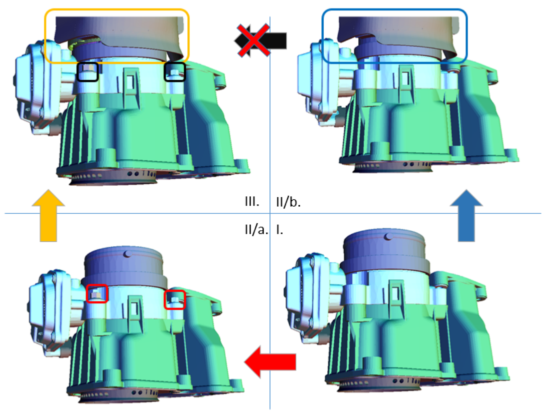

Fig. 4. The case study illustrates how different task sequences affect the feasibility of the assembly.

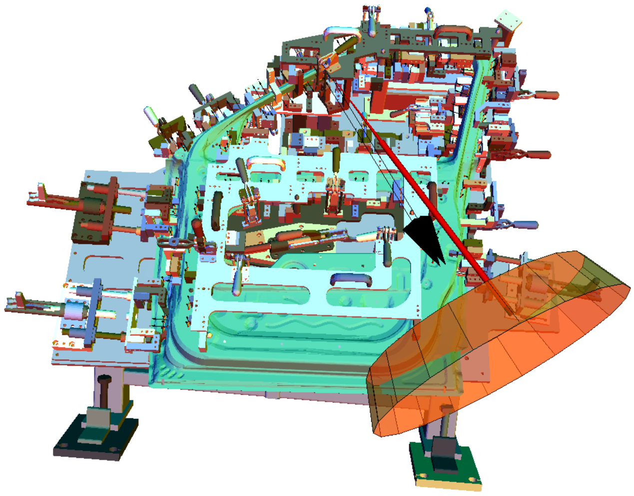

Fig. 5. Investigating the accessibility of a welding stitch (local geometric feasibility of an RLW feature) on a car door assembly. The red line shows a feasible, collision-free position of the laser beam (tool). The truncated cone is the set of scanner head positions that fulfill the technological constraints on focal length and incidence angle.

Fig. 4 illustrates the two alternative sequences of the tasks. Plan verification confirmed that the screwing first, placing second (states I.–II/a.–III.) sequence is feasible. However, the placing first, screwing second (states I.–II/b.–III.) sequence is infeasible, because the pneumatic screwdriver cannot access the screws when the resonator bottom is already placed. The proposed approach identified this ordering constraint by path planning to verify the geometrical feasibility of access to the screwing task, using the geometrical model of the screwdriver tool as well. It is highlighted that earlier approaches that consider parts as free-flying objects, but omit tools (e.g., [17]), could not identify this ordering constraint.

6.2. Remote laser welding of car door

In case of RLW, the tasks to be executed in the welding workcell include a series of pick-and-place operations to load the parts into the fixture, welding operations for each individual stitch in an arbitrary order, and finally, a single put-away task. Plan verification here can ensure feasibility from various points of view. Trivial technological constraints ensure that parts are loaded into the fixture before welding, and they are unloaded only at the end. Geometric reasoning guarantees that parts are loaded in the correct order. Nevertheless, the most important aspect for verification is that the welding features are locally feasible, i.e., the laser beam can access every welding stitch, see Fig. 5. Algorithms for stitch accessibility analysis have been presented in detail in [6].

7. Conclusions and future research

This paper proposed an approach to automated human-robot assembly process planning. It is based on a novel feature-based model of the assembly process, which can be synthesized from a standard CAD model of the product and the description of the applicable resources. Acknowledging that fully automated process planning is not possible using currently available representational and planning techniques, the paper focused on generating constraints that ensure plan feasibility, as well as on the formal verification of fully specified plans given as input. A brief outlook was also given on how the proposed verification techniques can be developed further to constitute the basis of a future automated assembly process planning system, which is the long-term vision of this research.

Acknowledgment

The authors are grateful for Gábor Erdős for his help in this work. This research has been supported by the EU H2020 grant SYMBIO-TIC No. 637107 and by the Hungarian Scientific Research Fund (OTKA), Grant No. 113038.

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