Thesis for the degree of Licentiate of Engineering

Planning of Robotic Assembly Sequences

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Göteborg, Sweden 2017

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Licentiatavhandlingar vid Chalmers tekniska högskola
Technical report No. R111
ISSN 1652-9243

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Typeset by the author using LaTeX.

Printed by Chalmers Reproservice
Göteborg, Sweden 2017

Abstract

In the automotive industry, short ramp up times and high product quality drive the product and production development of state-of-the-art solutions both in the research and industrial perspective. In addition to that, sustainable industry and society require optimized equipment utilization, in terms of materials used and consumed energy.

This thesis is a contribution in the never-ending process of achieving the goals above described and has as focus virtual product realization for quality and throughput, and, in particular, related to robot joining and assembly. Virtual methods, indeed, decrease the need for prototyping and can simulate, and thereafter optimize the robotic assembly process.

In order to optimize equipment utilization and assembly time for a new product or station, this thesis presents algorithms and tools to check geometrical feasibility and minimize cycle time in multirobot stations. The major contribution of this thesis is a new approach to schedule robot operations to avoid collisions and minimize cycle time for multirobot stations. Two articles present algorithms and tools to distribute the operations workload among several robots and coordinate them.

Robustness for the assembly process is important, therefore geometrical variation is also considered during path and assembly planning. In fact, one of the contribution is a method and algorithm integrating robot path planning and geometrical variation for robot assembly. The main idea is to let the robot move in the workspace areas where there is less uncertainty. Another part of the thesis integrates assembly design, sequence optimization and path planning, which can be used to evaluate different concepts regarding locating scheme and the robustness in the product critical dimensions.

The research presented and the corresponding implementations in software platforms is improving virtual product realization for robotic applications by requiring less time from the user and making automatic optimization not only part of delivering a detailed solution but also letting it be part of the decision making process.

Keywords: Assembly planning, robot routing and scheduling, path planning, geometrical variation, cycle time optimization.

Acknowledgments

I would like to thank my supervisors Dr. Johan Carlson at the Fraunhofer-Chalmers Centre (FCC) and Prof. Rikard Söderberg at the Department of Product and Production Development at Chalmers, for giving me this opportunity and for the guidelines, both technical and strategical, during the entire project.

I wish to extend my personal thanks to Dr. Robert Bohlin for his technical advises on many algorithms, and foremost on path planning. I would like to express my gratitude toward my colleagues at FCC for creating an inspiring environment.

Thanks to my family for always supporting me.

This work was carried out at the Wingquist Laboratory VINN Excellence Centre and is part of the Sustainable Production Initiative and the Production Area Advance at Chalmers University of Technology. It was supported by the Swedish Governmental Agency for Innovation Systems.

Domenico Spensieri

Göteborg, February 2017

List of Publications

This thesis is based on the following appended papers:

Paper 1. **Domenico Spensieri**, Johan S. Carlson, Fredrik Ekstedt, Robert Bohlin. *An iterative approach for collision free routing and scheduling in multirobot stations.* IEEE Transactions on Automation Science and Engineering, Vol. 13, 2, pp. 950-962, 2016.

Paper 2. **Domenico Spensieri**, Robert Bohlin, Johan S. Carlson. *Coordination of robot paths for cycle time minimization.* IEEE International Conference of Automation Science and Engineering, 2013.

Paper 3. **Domenico Spensieri**, Johan S. Carlson, Robert Bohlin, Rikard Söderberg. *Integrating assembly design, sequence optimization, and advanced path planning.* ASME International Design Engineering Technical Conferences and Computers and Information in Engineering Conference, pp. 73-81, 2008.

Paper 4. Johan S. Carlson, **Domenico Spensieri**, Rikard Söderberg, Robert Bohlin, Lars Lindkvist. *Non-nominal path planning for robust robotic assembly.* Journal of Manufacturing Systems. Elsevier, Vol. 32, Issue 3, pp. 429-435, 2013.

Other relevant publications co-authored by Domenico Spensieri:

Domenico Spensieri, Johan S. Carlson, Robert Bohlin, Jonas Kressin, Jane Shi. *Optimal Robot Placement for Tasks Execution.* Procedia CIRP, Vol. 44, pp. 395-400, 2016.

Johan S. Carlson, **Domenico Spensieri**, Kristina Wärmefjord, Johan Segeborn, Rikard Söderberg. *Minimizing Dimensional Variation and Robot Traveling Time in Welding Stations.* Procedia CIRP, Vol. 23, pp. 77-82, 2014.

Staffan Björkenstam, **Domenico Spensieri**, Johan S. Carlson, Robert Bohlin, Daniel Gleeson. *Efficient sequencing of industrial robots through optimal control.* Procedia CIRP, Vol. 23, pp. 194-199, 2014.

Domenico Spensieri, Johan S. Carlson, Robert Bohlin, Rikard Söderberg. *A method to optimize geometrical quality and motion feasibility of assembly sequences.* The 11th CIRP International Conference on Computer Aided Tolerancing, 2010.

Domenico Spensieri, Fredrik Ekstedt, Johan Torstensson, Robert Bohlin, Johan S. Carlson. *Throughput maximization by balancing, sequencing and coordinating motions of operations in multi-robot stations.* Proceedings of the 8th NordDesign Conference, Göteborg, Sweden, 2010.

Hugo Flordal, Martin Fabian, Knut Åkesson **Domenico Spensieri**. *Automatic model generation and PLC-code implementation for interlocking policies in industrial robot cells.* Control Engineering Practice, Vol. 15, Issue 11, pp. 1416-1426, 2007.

Avenir Kobetski, **Domenico Spensieri**, Martin Fabian. *Scheduling algorithms for optimal robot cell coordination - a comparison.* IEEE International Conference on Automation Science and Engineering, CASE 2006.

Hugo Flordal, **Domenico Spensieri**, Knut Åkesson, Martin Fabian. *Supervision of multiple industrial robots: optimal and collision free work cycles.* IEEE International Conference on Control Applications, 2004.

Contents

Part I

Introductory chapters

Chapter 1

Introduction

1.1 Background and motivation

Assembly planning is a complex process involving product design and production planning.

In this thesis the assembled products are studied. During the assembly design phase, besides functional requirements, geometrical variation is one of the important aspects to consider, together with assembly/disassembly issues.

In the manufacturing planning stage one aims to check feasibility (in terms of collision-free paths) of the operations, improve cycle time, and overall process robustness.

There are several types of assembly, categorized by the type of agent performing it and by the type of process joining the parts. Assembly operations can be done by humans, robots or other kinds of machines and include welding, sealing, gluing, fastening, and others.

The complexity of the operations themselves is added to the challenges deriving from the need to handle hundreds of parts. In fact, variation in the single parts and in the joining process may propagate yielding, in the worst case, a product that cannot be built at all or that does not satisfy the functional requirements.

A challenging sector where the market is very competitive and state-of-the-art solutions are needed is the automotive industry. Here a Body-in-White (BiW) consists of about 300 steel sheet metal parts, and the joining process by about 4000 spot welding points, see (Segeborn et al. 2014; Segeborn 2011). The workload is distributed among several stations and to hundreds of industrial robots. An example of an assembly line is depicted in Figure 1.1.

These impressive figures motivate the need for automatic tools that can be used to support engineers along the different phases. The main advantages consist in

- increasing product quality,
- decreasing commissioning times for production planning,
- improving the feasibility and cycle time in the implemented process.

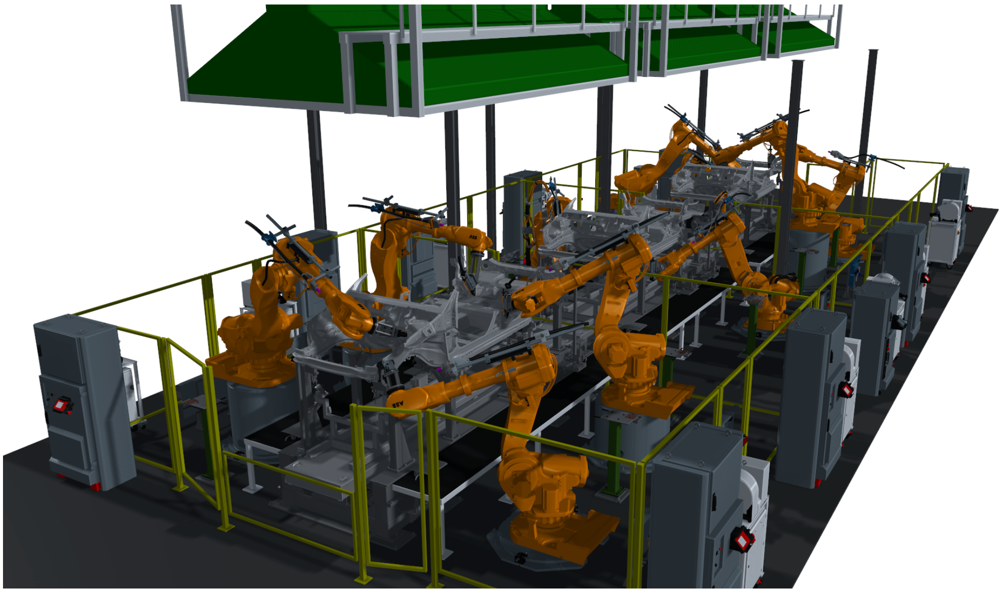


Figure 1.1: Assembly line in the automotive industry modeled in Industrial Path Solutions. Courtesy of Volvo Cars.

Moreover, by simulating in a virtual environment all these activities, there is less need to real prototyping, and time and quality for the overall planning have substantial benefits.

1.2 Scope

Assembly planning is a large research area, including the design of the assembly, the definition of its functional and other requirements, the definition of the single tasks to assembly the product and the optimization of such assembly operations. Often, robots are part of the assembly process and, due to their still complex programming, automatic planning is highly important.

In this thesis the focus is on geometry assurance, path planning, and sequencing topics. Indeed, these research subjects are the real enablers for efficient virtual product realization and are deeply studied in both the academic and the industrial communities. The main goal is to integrate such topics to solve problems requiring inter-disciplinary competences and the focus is on methods and tools for planning sequences, from a geometric, equipment utilization, and logic perspective.

The platform where many methods are developed is the software Industrial Path Solutions, (Industrial Path Solutions 2017) which provides many useful functionalities such as proximity queries, robot path planning, and optimization routines.

Moreover, the software platform RD&T, (RD&T 2017) has been used in order to model and perform analyses related to geometrical variation.

The algorithms developed assume and are limited to rigid body part assembly: in fact, the deformation of parts will not affect the results, therefore flexible parts, such as cables and hoses, are not considered. For state-of-the-art simulation within the area see (Hermansson, J. S. Carlson, et al. 2013; Hermansson, R. Bohlin, et al. 2013; Hermansson, R. Bohlin, et al. 2016).

Furthermore, since the target application is off-line simulation, the algorithms and methods are not devised to run on real-time controllers or on-line environments. However, solution quality and computational performance are still a main goal.

1.3 Research methodology

The research carried out during the projects contributing in this thesis relates to engineering design research, and follows what is known as Design Research Methodology (DRM), see (Blessing and Chakrabarti 2009).

According to the DRM, the research activities and method should be divided into four stages consisting of a criteria formulation and three studies. These stages can be done sequentially or iteratively for successful results. In particular:

- **Criteria definition**: identify the aim that the research is expected to fulfill by means of *measurable success criteria*. In this work they are: being able to automatically obtain high quality (for example w.r.t cycle time and geometrical robustness) solutions for industrial problems and decreasing commissioning time for the engineers.

- **Descriptive study I**: identify the factors influencing the above criteria and to provide a reference model or theory to improve design. In this work literature studies have been carried out and research and industrial gaps identified.

- **Prescriptive study**: develop an impact theory or model as basis for systematic development of methods, usually aiming at a proof of concept. In this work some existing theories have been adopted and further developed, as well as new models have been devised for some of the problems encountered. Algorithms have been implemented at prototype level.

- **Descriptive study II**: identify whether the methods and tools can be used in the intended situations (*application evaluation*), and how it fulfills the success criteria (*success evaluation*). In this work the implemented methods are evaluated towards literature, random, and industrial cases. For some algorithms a comparison with existing ones is carried out.

This thesis work has been done within the Wingquist Laboratory, see (Wingquist Laboratory 2017), and its VINNOVA excellence centre: Wingquist Laboratory VINN Excellence Centre, see (Wingquist Laboratory VINN Excellence Centre 2017). The centre focuses on virtual product realization and research topics are formulated based on a scientific challenge and an identified industrial need.

In addition to traditional scientific results like academic publications, and according to the DRM described above the research projects also result in a demonstrator (a suggested functionality or working procedure) developed by the research team, see Figure 1.2 for the different components of a successful project within the Wingquist Laboratory.

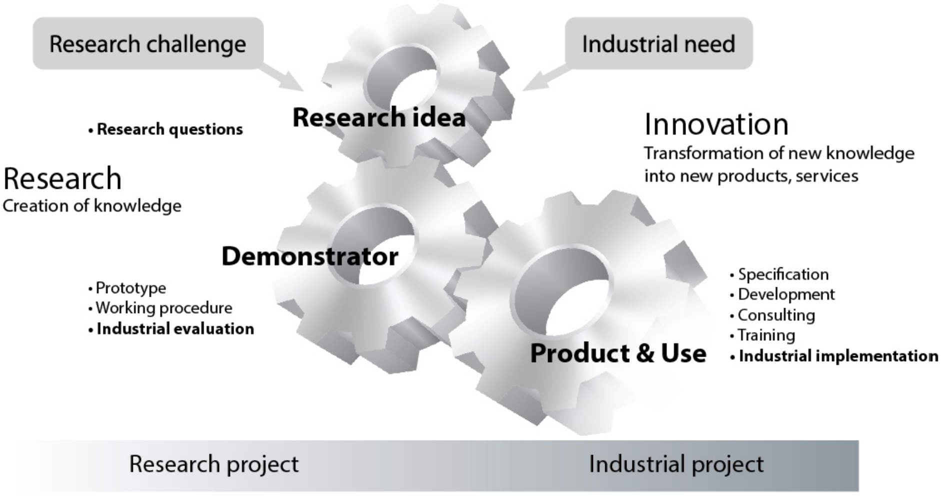


Figure 1.2: Wingquist Laboratory research strategy

1.4 Research questions

By following the Wingquist Laboratory strategy, here a summary of the research questions is presented

RQ1: How can the equipment utilization of multi-robot stations be improved?

RQ2: How can robots avoid collisions when executing predefined robot programs, in a way that cycle time is minimized?

RQ3: How can possible assembly sequences and subassemblies be generated and verified to be feasible?

RQ4: How can geometrical variation be considered during collision free robot path planning?

1.5 Contributions

The contributions of this thesis are below stated.

Scientific contributions

- A decoupled method and corresponding algorithms are devised to minimize cycle time in multirobot stations, (Paper 1). The method balances the load among the robots and avoids mutual robot collisions by velocity tuning. This tuning is done by a novel algorithm of high performance (Paper 2).
- A method integrating assembly design, sequence optimization and path planning. The method is capable of optimizing an assembly sequence based on geometrical quality measure (Paper 3).

- A method and corresponding algorithm to perform robot path planning in presence of geometrical variation and robot uncertainties (Paper 4).

Industrial contributions

- A high performance implementation for robot coordination, well suited for algorithms running it repeatedly.
- A prototype tool to generate optimized assembly sequence from CAD models and locating scheme.
- A prototype tool to generate collision free robot motions in presence of geometrical variation and robot uncertainties. This triggered industrial end users to start using path planning considering geometrical variation.

1.6 Outline

This thesis consists of two parts.

Part I is a general introduction to the field and puts the appended papers into context. After this introduction, a description of the problems treated is given in Chapter 2: here, the problems are stated and their related research questions are restated. In the following Chapter 3, the background for the algorithms used is presented. In Section 3.1, there is an introduction to the sequencing and scheduling problems encountered in this work. In Section 3.2 the concepts of locating scheme and geometrical variation are introduced. A short reference to path planning is also presented, in Section 3.3. Thereafter, the main applications and the results are described in Chapter 4. In the final Chapter 5, a discussion on the overall problems, results, limitations and future work is presented.

Part II contains the appended research papers constituting the main contribution of the thesis.

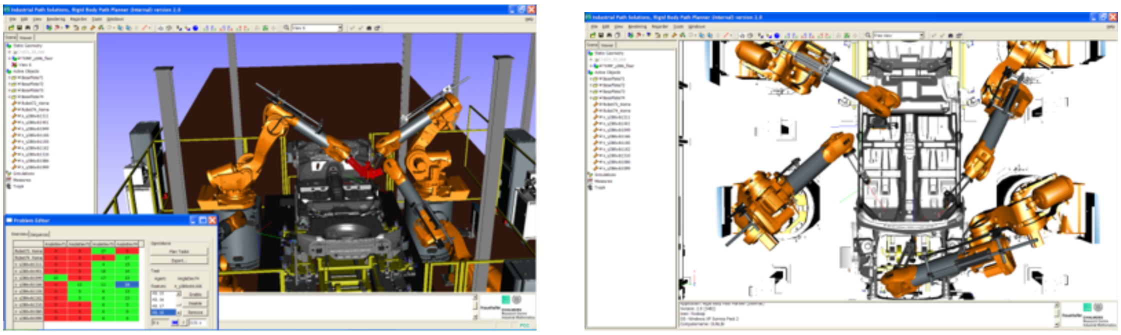
Chapter 2

Problems description

2.1 Robot joining sequences optimization

In the automotive industry, during the assembly process, the car body is usually assembled together on a line where several stations are placed serially and in parallel. At each station multiple robots perform operations like stud, spot welding, and sealing, and often share the same workspace.

In this framework the main concern is the problem of maximizing the number of units assembled in a line. This can be directly translated into minimizing the time needed at each station to perform the predefined tasks in a collision-free way.



(a) Task planning in IPS

(b) Multirobot solution in IPS

Figure 2.1: Task planning and load balancing in IPS

The challenge, at each station or along the whole line, is to concurrently:

- distribute the tasks among robots such that each of them is assigned to one robot (set partitioning, dispatching),
- decide in which way each robot should perform a task among several configurations,
- find a sequence of tasks for each robot (routing),
- compute robot paths that are collision-free w.r.t the static environment (path planning),

- schedule the sequences of paths such that no collision occurs among the robots (scheduling).

The problem in its entire complexity is very interdisciplinary, integrating together combinatorial optimization and path planning issues, see (Rambau and Schwarz 2014; Landry et al. 2013). Moreover, only in the last years, with the development of computers and software tools, it has been possible to face large problems in a reasonable time. In Figure 2.1a a screenshot from IPS shows how the different tasks can be performed by four robots and in Figure 2.1b a screenshot of a solution computed by the same software.

So, a relevant question can be formulated:

RQ1: How can the equipment utilization of multi-robot stations be improved?

2.1.1 Robot path coordination

In many industrial applications, robots are often constrained to move on fixed geometrical paths, see AGV on fixed tracks (Olmi et al. 2008), robots are executing fixed motions in space (Siméon et al. 2002). A similar problem arises also in air traffic management, see (Pallottino et al. 2002).

Moreover, the assumption of having fixed paths is often used in solving more complex problems that are prohibitive from the computational point of view: in these approaches, the problem is decoupled into simpler subproblems, which are solved separately and coupled together according to some strategy.

In this work we focus on coordinating robot paths sharing a common environment in order to minimize cycle time, by avoiding their mutual collisions. In other words, the paths are fixed in the robot configuration space, but their motion trajectories, i.e. path in time, are not yet defined. The goal is to introduce waiting times or slow down the robot motions, to avoid mutual collisions and to optimize cycle time. In Figure 2.2 a screenshot from IPS shows a collision between two robot motions.

The second research question, addressing this problem is.

RQ2: How can robots avoid collisions when executing predefined robot programs, in a way that cycle time is minimized?

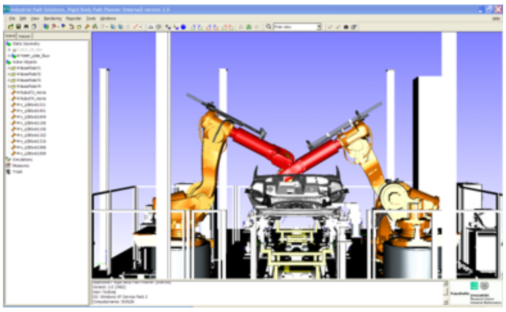


Figure 2.2: Collision between two robots along their defined paths.

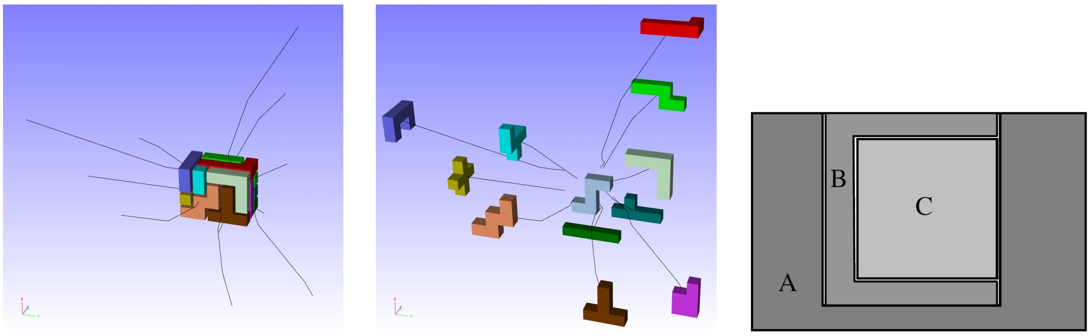
2.2 Assembly planning

Assembly design consists in modeling mating features among parts such that the final product has the desired quality robustness and fulfills its functional requirements, see (Whitney et al. 1999). The mating features define how single parts in the assembled product (or assembly) are coupled to each other and influences the product key characteristics, see (Mantripragada and Whitney 1998).

Assembly design strategies oriented toward the assembly process are studied under the general research area Design for Assembly (DFA), see (Boothroyd 2005). Since DFA strives to consider assembling the product, already at the design phase, a lot of efforts has been put into defining more in detail assembly plans, from the geometrical and sequencing point of view. While investigating the feasibility of such sequences, the key question that arises is whether assembly operations are geometrically feasible.

Tools addressing assembly design and feasibility issues are often well separated and used at distinct phases of product realization. However, they heavily rely on each other, since the assembly order defines the geometrical feasibility and features design constrains the assembly order, see (Defazio and Whitney 1987; Wang and Ceglarek 2007).

In fact, a typical problem that needs to be faced is which parts, during the assembly plan, should be assembled together before others, in order to fulfill design constraints and geometrical feasibility. In Figure 2.3a and 2.3b the Pentomino puzzles illustrates a typical benchmark for assembly/disassembly planning, and in Figure 2.3c it is illustrated a two dimensional example where parts B and C need to be assembled together before moving them into A, due to geometrical conflicts.



(a) Pentomino puzzle assembled

(b) Pentomino puzzle disassembled

(c) A 2D 3-parts assembly that cannot be assembled linearly on part A

Figure 2.3: Assembly sequencing basic issues

Therefore, we study how to integrate these areas in order to provide a valuable tool for engineers for a more efficient virtual product realization.

The third research question is the following:

RQ3: How can possible assembly sequences and subassemblies be generated and verified to be feasible?

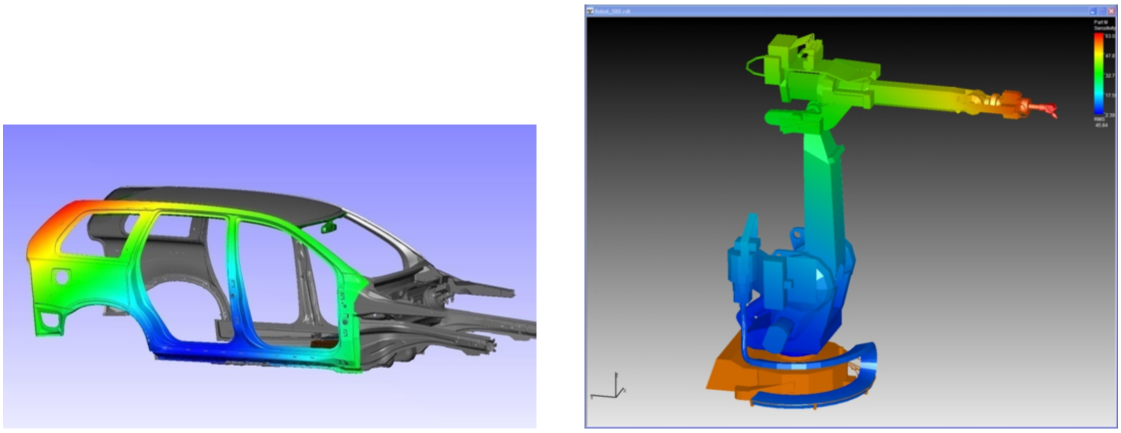
2.3 Non-nominal robot path planning

A common scenario when simulating manufacturing and assembly processes includes an engineer trying to simulate the process by manipulating objects in a digital mock-up software. In highly geometrical restricted assembly situations, this procedure is often sensible to errors and is time consuming, and becomes even more complex when the assembly tasks are performed by robots. An automated verification is therefore helpful, since it can decrease the enormous costs that arise when realizing the infeasibility of an assembly plan late in the production phase.

Furthermore, every physical object is subject to geometrical variation due to its manufacturing process, therefore even robots, treated as assembled products, are. Moreover, robots are also negatively affected by resolution issues due to their sensors and actuators. This fact influences their accuracy and resolution, therefore adding even more uncertainty to an assembly system. In Figure 2.4 it is color coded how variation propagates for an industrial robot and the side of a car where it is supposed to mount the driving unit. Due to the small door opening compared to the size of the robot arm and the driving unit, this case is very challenging.

A relevant research question addressing these problems is the following:

RQ4: How can geometrical variation be considered during collision free robot path planning?



(a) Variation simulation for car side

(b) Variation simulation for assembled robot at its home configuration

Figure 2.4: Variation simulations for a car side and an assembled robot in a specific configuration.

Chapter 3

Frame of reference

3.1 Sequencing in robotic assembly

Product assembly consists of several operations that may be done by a number of agents, such as industrial robots, AGVs, human beings, etc.

The order in which operations are performed may influence the product quality and production cycle time. Moreover, the process has restrictions based on the agent performing it (*e.g.* some operations may increase the robot wear, or are not ergonomically suitable for a human being), and based on process specific constraints such as locating scheme or minimum safety distance towards the environment.

These constraints further complicate the problems. The goal of planning robotic assembly sequences is to optimize the order in which such operations are done, by considering the most important sequence measures for the assembly. In this thesis the focus is on minimizing cycle time and, secondly, on optimizing their robustness with respect to geometrical variation.

3.1.1 Single agent sequencing

When cycle time for an agent is considered, problems can often be modeled as a Traveling Salesman Problem (TSP).

As it is well known, this is one of the most intensively studied problems in combinatorics: given a set cities and distances between them, the problem is to find the shortest tour (returning to the start city) visiting all cities once.

The decision version of it belongs to the class of NP-complete problems, see (Garey and Johnson 1990). Therefore, it can be solved to optimality for small, medium sized problems, whereas large instances are nowadays solved, without proof of optimality, by powerful heuristics.

There exist several variants foe the TSP, for an overview see the book (Gutin and Punnen 2002), which may add some constraints or may slightly modify the definition. For example, precedence constraints between cities might be introduced, transforming it into the well known Sequential Ordering Problem (SOP), see (Escudero 1988).

A very useful generalization of the TSP is the Generalized Traveling Salesman Problem (GTSP), where cities are clustered into groups and the goal is to find the minimum cost tour visiting exactly one node in each group, see (Laporte et al. 1987).

Many of these variants can be solved by a transformation into a TSP with artificial cities, see (Noon and Bean 1993), whereas for others no such transformations are known and problem specific algorithms are required.

In robotic assembly, optimizing the cycle time for a single robot that needs to perform a set of tasks can be modeled as a GTSP:

- each stud/welding task can be modeled as a group and the different configurations the robot can assume to perform the task can be modeled as cities in the group,
- the motion time between robot configurations defines the distance between cities.

The optimal sequence of tasks and the corresponding optimum cycle time are given by solving the relative GTSP. However, sometimes, a single robot does not match cycle time requirements, or it is impossible to put all tasks in the robot workspace. In these cases, several robots are needed. Multirobot lines can be optimized by using Multiple GTSP (MGTSP) models.

3.1.2 Multiple agent sequencing

In a Multi TSP (MTSP), each city should be visited once by one of the multiple salesmen, see (Toth and Vigo 2002). As more studied similar problem is the Vehicle Routing Problem (VRP), see (Toth and Vigo 2002).

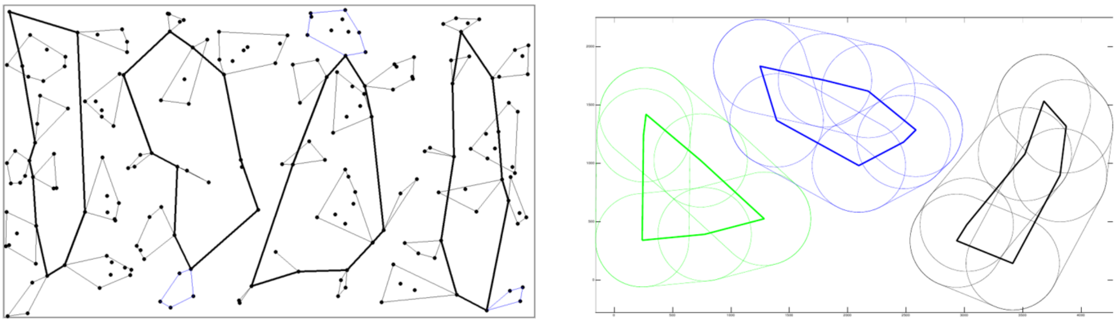
The most common used objective function in its mathematical programming formulation is to minimize the sum of distances each salesman travels.

However, in the automotive process, the goal is to minimize cycle time, therefore in the applications considered in this thesis the focus is to minimize the largest distance traveled by the salesmen. This modification adds complexity to the problem since many different solutions have almost equal values. If the GTSP model is also introduced, then one ends up in studying the Multiple GTSP (MGTSP) with min-max objective function. Also here, exact solutions are limited to small sized instances, and heuristics are needed to solve real world ones, see Paper 1.

These models do not catch the fact that there might be conflicts (usually geometrical collisions) between agents moving from one group to another. This extra condition drastically complicates the problem.

3.1.3 Multiple agent sequencing with conflicts

When collisions are present, the problem can be tackled from a completely different perspective: looking at it as a multidimensional path planning problem where the degrees of freedom for each agent are summed together and thereafter adding the combinatorial nature for sequencing. However, this model results in models for



(a) Graph representation of a MGTSP

(b) Graph representation of a MGTSP with some conflicting edges

Figure 3.1: MGTSP without and with conflicts

which the current direct algorithms are not able to find enough good solutions in a reasonable time, see Ch. 7 in (LaValle 2006).

Therefore, decoupled approaches are used. Two of the most suitable methods for the goal in this thesis are to avoid conflicts by

- rerouting the agents, therefore changing the order of cities,
- introducing waiting times along the paths.

In this way, the agents won't be in the same area at the same time. When the first approach is used, the problem can be approximated as a single agent sequencing one. Indeed, in Paper 1 the problem is transformed into an artificial GTSP, whose solution provides a suboptimal cycle time for a collision free multi agent system.

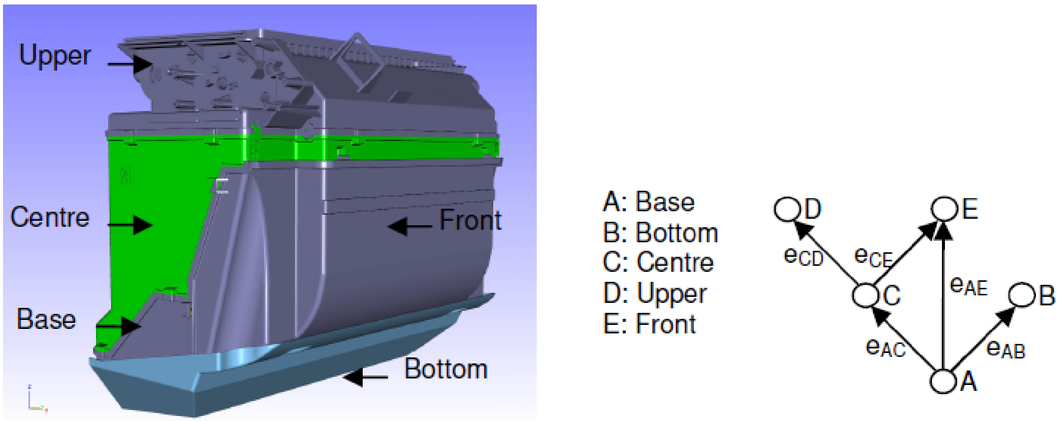
The second approach, on the other hand, may be incorporated in iterative algorithms exploiting the time aspect to make conflicting sequences into collision free ones, see also (Rambau and Schwarz 2009). The problem of introducing waiting time on predefined path in order to avoid collisions is called Path Coordination Problem (PCP), and is investigated in Paper 2. It is very similar to scheduling problems, therefore algorithms based on longest paths and branch and bound can be tailored to efficiently solve it, see (Blażewicz et al. 2000).

3.1.4 Assembly sequences

Different types of parts assembly are classified, based on the need of several agents performing them, on the need of intermediate configurations, and other criteria.

In this perspective notions as the Datum Flow Chain (DFC) have been proposed, see (Mantripragada and Whitney 1998). In this work, a similar concept is considered, namely the locating scheme which may be seen as a particular case of the DFC. Indeed, contacts between parts are not considered, but only mates.

Information about the locating scheme, see (R. Söderberg, Lindkvist, and J. S. Carlson 2006), can be extracted in order to deal with assembly planning, sequencing particularly, and may be defined by a directed acyclic graph (DAG), where nodes represent atomic parts, and edges between nodes represent the existence of mates between the corresponding parts. See Figure 3.2 for a possible locating scheme for a climate unit.



(a) Climate unit assembly consisting of 5 parts

(b) Locating scheme for the climate unit on the left

Figure 3.2: Climate unit and its relative locating scheme.

Assembly sequences may be explicitly represented by directed graphs or by AND/OR graphs, see (L. H. d. Mello and Sanderson 1986). These are the two main approaches used.

Direct graphs exploit the property that a product is assembled when all the contacts among its parts are established. This means that the configuration of parts is given by the contacts established. Therefore, a state for a product consisting of n parts can be represented by an n-dimensional binary vector. An edge connecting two nodes corresponds to the establishment of one or more connections.

The other state space perspective is to look at one state as a partition of the initial set of parts. In AND/OR graphs each node represents a subset of the initial set of parts. An edge in these special graphs is called hyper-arc and connects one node to two other nodes. Namely, it represents the decomposition of the assembly associated to the first node into the two subassemblies associated to the two target nodes.

The equivalence of the two representations and with other implicit ones is discussed in (L. d. Mello and Lee 2012).

The search for an optimal sequence can be computed through the A* algorithm in the liaison space, (Nilsson 1980) and the AO*, (Martelli and Montanari 1973) in the part based one.

3.2 Geometrical variation in robotic assembly

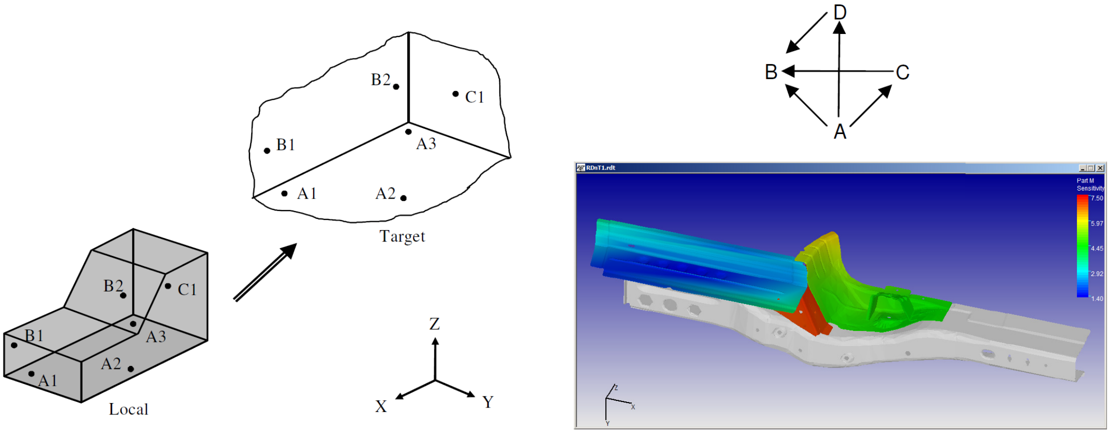
3.2.1 Robust design

During products assembly, many problems may arise due to parts not being in their nominal shape and due to key product dimensions not being respected. The fulfillment of such critical assembly requirements, functional and purely geometrical, depends on:

- how the single parts are manufactured,
- the conceptual design solution for parts assembly,
- how the actual assembly operation is performed.

Therefore, integrated geometry assurance tools supporting the engineers during early concept phase, verification, and production phases are highly motivated.

At the concept phase, the purpose is to generate designs insensitive to variation to their input parameters, a discipline well known as robust design and geometry assurance, see (R. Söderberg, Lindkvist, and J. Carlson 2006). The main concept used is to model the assembly through the *locating scheme*, (Rikard Söderberg et al. 2006): it consists of defining how single parts are put together, by means of *locators*. Each part (considered as a rigid body here) has to be locked in all its six degrees of freedom by the locators. An extensively used type of locating scheme is the orthogonal 3-2-1 system. Here, three primary locators lock 3 dofs (TZ, RX, RY), two locating points lock 2 dofs (TX, RZ) and the last one constrains the remaining translation (TY), see Figure 3.3a.



(a) Orthogonal 3-2-1 locating scheme

(b) Locating scheme and variation simulation for a 4-parts assembly

Figure 3.3: Orthogonal 3-2-1 locating scheme and variation simulation for a 4-parts assembly

In order to evaluate the robustness of the design, two main analyses are usually carried out at this phase, namely the stability analysis and variation simulation, (R. Söderberg, Lindkvist, Wärmefjord, et al. 2016).

The stability analysis applies virtual displacements to the locating points and computes the resulting variation on the whole assembly, fulfilling all predefined mating conditions. In other words, it evaluates the geometrical robustness of a concept, by estimating how variation in the locators propagate to the entire assembly. Available tools performing this analysis are in the software RD&T, (RD&T 2017).

The variation simulation generates disturbances for all input parameters, according to defined distributions, and builds distributions for critical product dimensions. This analysis is also present in RD&T: here, the method captures non linearities and allows any kind of distributions of the input parameter variation. Moreover, it is also possible to get an overall picture of a concept by color coding the parts geometries. See Figure 3.3b for an example on a conceptual locating scheme for a 4-parts assembly where the gray part serves as a base or fixture. Based on these analyses, geometrical assembly sensitivity can be compensated by an appropriate selection of manufacturing tolerances.

However, besides reducing the variation of incoming parts, overall variation can be reduced also by optimizing the locating schemes.

After the concept phase, inspection preparation and root cause analysis, (J. Carlson and R. Söderberg 2003) can be performed, at the verification respectively production phases, in order to achieve an effective product realization. In this thesis the focus is on rigid body assembly variation at the design phase, both for single parts (not flexible) and robots. These concepts are a main component in many of this thesis contributions. They are used to limit the search for assembly sequences and to estimate uncertainty in robot motions.

3.2.2 Robot uncertainties

An industrial robot usually consists of a number of links joined by actuated joints. By considering the links as rigid bodies, it is possible to build an assembly model of the robot, see (Lindkvist L. 2007). Depending on the geometry of the joints, this model can be done in a number of ways. Here, the most common type of joint is considered, namely the revolute joint. One type of revolute joint consists of an axis rotating relative to two holes in a yoke. The position of the part connected to the axis is determined by the contacts between the axis and the holes. A locating scheme is artificially created to model this construction, and one of the locators does not represent a physical contact but can be used to introduce variation in the angle of the joint, see Figure 4.3a which is determined by the actuators.

3.3 Path planning in robotic assembly

The problem of finding collision free motions for different types of agents is central in several applications, e.g. assembly, industrial and mobile robotics, digital characters animation and simulation, surgery, and molecular biology. In this work the focus is on rigid body and robotic assembly and, as stated in Section 1.2, on off-line algorithms for planning. For detailed overview on the topics, see (Latombe 1991; LaValle 2006).

3.3.1 Configuration space

The problem in its simplest form can be stated as: finding a continuous path for an agent, from a start pose to a goal pose, avoiding collisions with the environment.

Even if the agent workspace is the 3D world that we are used to, anyway planning collision free motions is done in the *configuration space* and the obstacles present in the environment are mapped into that. The configuration space for a given agent is the space of all possible configurations that it may assume. For a rigid body, it consists of its placement in space, defined by a three dimensional vector, and of its 3D orientation, which may be defined by Euler angles, rotation matrices, quaternions, etc. A three dimensional vector is an element of R^3, and a 3D rotation is an element in $SO(3)$. Therefore, all possible configurations for a rigid object (*a.k.a.* free floating body) are the elements of $SE(3) \cong R^3 \times SO(3)$. For a typical industrial robot, consisting of a serial kinematic chain of six revolute joints, the configuration space C is the product of all single joint spaces C_i. Therefore, if each joint has the full range of motion in $[0, 2\pi)$, then $C_i = S^1$, thus $C = S^1 \times S^1 \times \ldots \times S^1$. It is also common to use $C \cong R^6$. Thus, a robot configuration is represented by a point in the configuration space.

In order to plan collision free motions, the environment needs to be mapped onto the agent configuration space as forbidden areas. This mapping can be done by placing the agent in several configurations and checking whether a collision occurs or not.

The problem of collision detection in 3D is a wide research area in computational geometry in itself, see (Lin et al. 1996), so here a brief overview is given. Fast collision detection algorithms are a core functionality for motion planning in virtual environments.

3.3.2 Collision detection

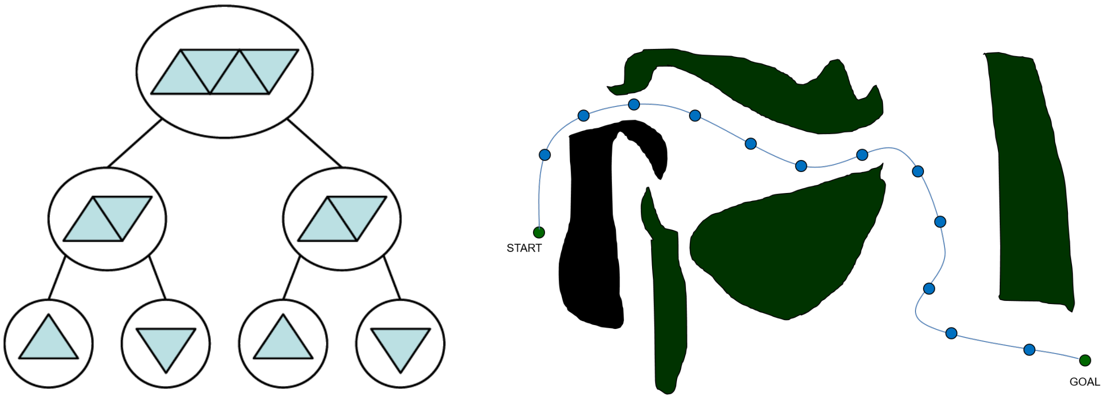
Objects in virtual environments are often represented by primitives like triangles, polygons, nurbs, etc. These objects may contain millions of triangles and be very complex, therefore just checking pairwise primitives for collision is impractical. Moreover, besides collision detection, it is very important to compute both exact and approximate distances. A powerful approach to carry out that uses hierarchical bounding volumes (HBV) to model objects and different techniques have been devised to traverse these hierarchies.

A bounding volume (BV) is used to contain sets of geometric primitives. In order to model the desired accuracy a tree of BVs is used. Children of a BV contain partitions of the parent BV, and the leaf nodes of the tree contain one primitive, a triangle for example.

The query for collision starts by comparing the roots BV for each object. If these overlap, then the query is applied recursively to their children. Otherwise, if no overlap is present, then the algorithm returns that no collision occurs. If a leaf node is involved, then collision test is done directly on it. Exact and approximate distance computations proceed in a similar way.

The choice of the BV, of how to traverse the tree, and of other design parameters control the performance of these algorithms for different scenarios.

Even if performance may vary consistently among different approaches, anyway, in practice, these tests constitute the heaviest part from the computational point of



(a) Bounding Volume Hierarchy concept illustrated

(b) Smooth path from start to goal in configuration space with obstacles

Figure 3.4: BVHs and collision free continuous path in configuration space

view, when planning collision free motions.

Having distance queries available as a routine enables mapping obstacles onto the configuration space for the defined agent. Thus, planning a continuous path from start to goal configuration can be done.

3.3.3 Planning

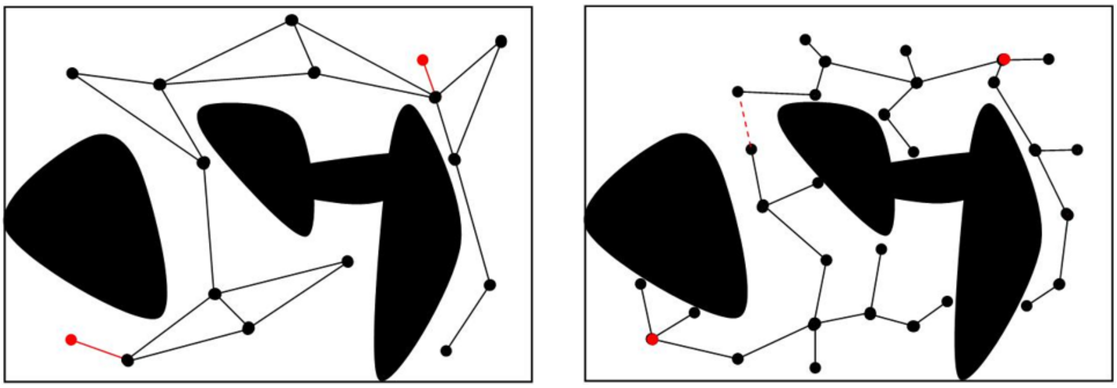
The path planning problem, even for a polyhedral agent, is exponential in the dimension of the configuration space, see (Canny 1988). Therefore, in practice, approximations are used: heuristic algorithms trade off completeness for practical efficiency.

One of the most used and successful techniques is based on sampling the configuration space and searching for a path connecting the samples in a collision free way, see (Karaman and Frazzoli 2011) for an overview. The main algorithms adopted in this class are undoubtedly the Probabilistic RoadMap (PRM), see (Lydia E Kavraki et al. 1996) and the Rapidly-exploring Random Trees (RRT), see (Lavalle et al. 2000). These two approaches differ in the way sampling is done and on how they construct the graph.

The PRM family of algorithms first constructs a graph (or roadmap) of collision free paths, see 3.5a. Then, a shortest path is computed, connecting the initial to the goal configuration. The first phase well suits multiple collision queries.

On the other hand, single queries are used in the family of RRT algorithms. They incrementally build a tree of feasible paths, trying to connect the samples in a collision free way, see 3.5b.

When a graph is built, then it is possible to search for improved paths, according to some measure, by using graph search algorithms. The most influential one in the motion planning research area is definitely the A*, see (Nilsson 1980). This is a variant of Dijkstra algorithm, where additional information guides the search toward promising area of the configuration space. Indeed, from a given configuration, an estimate of the cost to the goal configuration is added, such that large part of



(a) Probabilistic RoadMap (b) Rapidly-exploring Random Tree

Figure 3.5: Sampling based path planning techniques

the state space can be skipped, therefore substantially improving computational performance.

Even if several search techniques can decrease computing times, the most expensive part is still collision testing. In order to cope with that, a very powerful approach is adopted in practice: collision test is performed only when really needed in an attempt to delay it, see (Robert Bohlin and Lydia E. Kavraki 2000; Robert Bohlin 2001).

Path planning is a main component in all contributions of this thesis. It is used to detect feasibility of rigid body assembly paths, to estimate robot travel times in presence of obstacles, and to compute robust robot motions less sensitive to geometrical variation and robot uncertainties.

Chapter 4

Contributions and results

This chapter provides an overview of the main contributions of the thesis. For a more exhaustive description of algorithms, methods, and tools, please refer to the appended papers in Part II.

4.1 Robot joining sequences optimization

In Section 2.1, the problem of optimizing robot joining sequences has been described and the following research question has been formulated:

RQ1: How can the equipment utilization of multi-robot stations be improved?

This general research challenge can be tackled at different levels. Here a contribution toward optimizing cycle time is proposed, when a set of pre-positioned robots and a set of pre-defined tasks are given.

First, an exact method is proposed to solve small problems without collisions. The problem is modeled as a min-max MGTSP, see Section 3.1.2. Since the target instances are small sized (4 robots, about 30 tasks), the problem is solved by an exact branch and bound algorithm, where different lower bounds are presented, combining the solutions of a min-max set partitioning problem and of a GTSP, see Section 3.1.1.

Then, collisions are introduced and the assigned robot tasks are sequenced and scheduled with the aim to avoid conflicts. This problem is approached by assuming that robots move synchronously, *i.e.* each robot operation starts and stop at the same time. A novel transformation of this synchronous problem into a GTSP is presented. When a solution is obtained, the synchronous assumption is relaxed, a fixed sequence constraint is introduced and the robot paths are scheduled to further improve cycle time.

Finally, in order to provide complete robot solutions, path planning functionalities are introduced, allowing the robots to avoid collisions with the static environment and among themselves.

These steps are iterated until a satisfying solution is obtained. Experimental results are shown for both problems and for their combination. The algorithm is applied to a test case adapted from welding applications in the automotive industry.

Results for the first part are good, achieving all robots to have a minimum workload. The successive synchronous part is able to solve the problem and works well in combination with the robot coordination post-processing.

A prototype tool has been implemented on top of the software platform IPS. It remains to evaluate on which types of instances the method can be preferred to existing heuristic ones.

See Paper 1 for a more extensive and detailed presentation.

4.1.1 Robot path coordination

A core problem to be solved in order to efficiently run the above method is the path coordination problem (PCP), see 2.1.1. This was also introduced as a standalone problem to answer the research question:

RQ2: How can robots avoid collisions when executing predefined robot programs, in a way that cycle time is minimized?

An exact algorithm is proposed. The problem is modeled in a way similar to the job shop scheduling problem and a branch and bound (B&B) approach is tailored to solve it in order to give high computational performance, also on typical desktop machines. The structure of the problem presenting only pairwise robots collisions (see Figure 4.1) is exploited to achieve tight lower bounds in the B&B. Here, pairwise collisions areas are illustrated for a three robots case. The black line is one of the possible paths from start to goal, representing a time scaling for the robots trajectories.

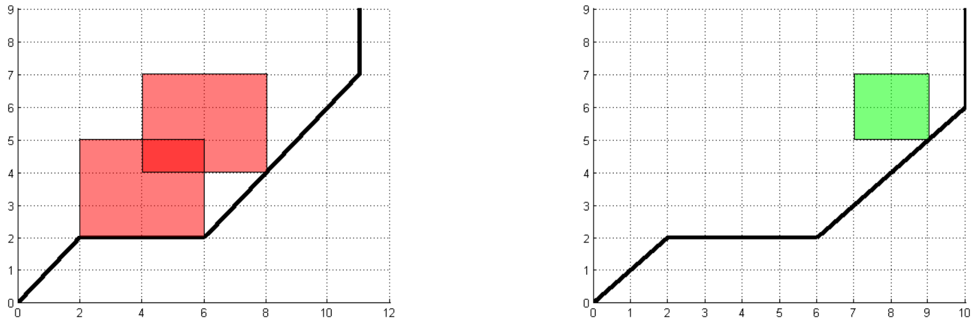
The mentioned good computational performance can also be achieved due to the objective function enabling the use of longest path algorithms in Directly Acyclic Graphs (DAGs) for its evaluation.

The high speed property particularly benefits solution approaches where this subproblem is the inner phase of more complex ones, as in the decoupling approach introduced in Section 2.1.

A computational study on random and industrial test cases shows its superiority over an open source Mixed Integer Linear Programming solver, used with its default settings.

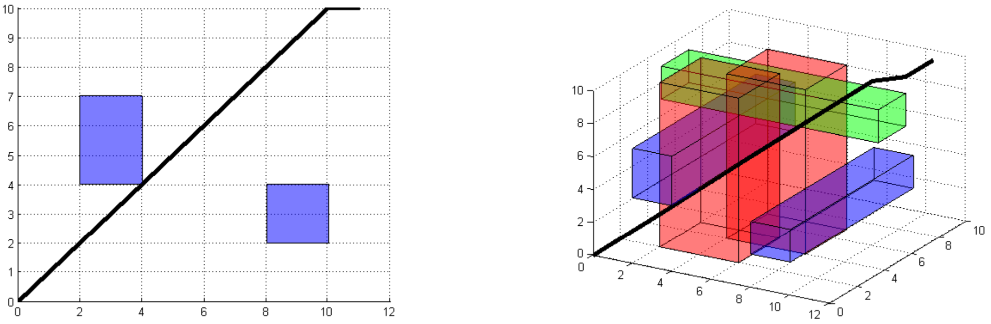
A prototype tool has been implemented in the software platform IPS. Due to the successful results on the extensive tests, a product implementation is ongoing.

For a more exhaustive algorithm description please see Paper 2.



(a) Coordination diagram for R^1 (horizontal) and R^2 (vertical).

(b) Coordination diagram for R^3 (horizontal) and R^2 (vertical).



(c) Coordination diagram for R^1 (horizontal) and R^3 (vertical).

(d) Generalized coordination diagram for R^1, R^2, and R^3.

Figure 4.1: Generalized coordination diagram for test case with 3 robots and 5 collision zones.

4.2 Assembly planning

Sequencing robot operations for sheet metal assembly has been done assuming all parts were at their final positions. Anyway, the order in which parts are assembled together is not a trivial task. Indeed, it is influenced by the geometrical feasibility of the assembly operation and by the locating scheme of the product.

A method, algorithms and tool integrating assembly design, sequence optimization and rigid body path planning is described in Paper 3, to answer the research question in Section 2.2:

RQ3: How can possible assembly sequences and subassemblies be generated and verified to be feasible?

The state space of possible assembly sequences is explored and a rigid body path planner is used to verify geometrical feasibility and to give the assembly operation a quality measure.

Moreover, a locating scheme, predefined for the assembly, is considered and limits the search space. One of the main advantages is the use of a global path planner, instead of one only based on local motions.

The algorithm is able to identify the possible subassemblies, both from the geometrical feasibility point of view and respecting the constraints imposed by the locators. Moreover, every assembly sequence can be given a quality measure and a global assembly sequence can be optimized.

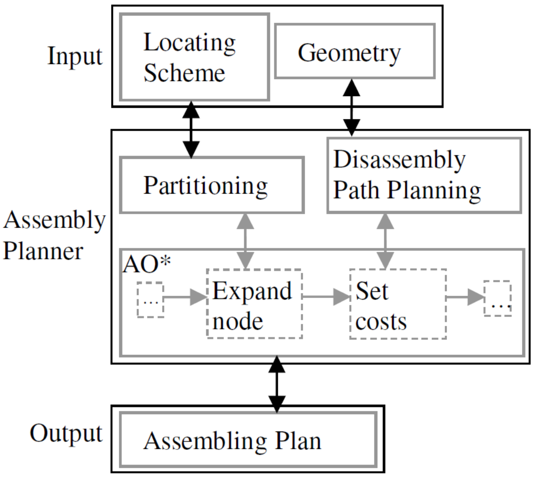


Figure 4.2: Interconnection of different modules for assembly planning

In Figure 4.2 the different algorithmic components of the method are depicted. It is possible to note that the sequencing part only includes creating partitions based on the design concept (locating scheme) and the sequences are verified and given a cost by a path planner working in the CAD models. Please, refer to Paper 3 for a more detailed description. This method assumes a pre-defined locating scheme and can be used as a simulation tool to evaluates different concepts w.r.t. assembly robustness. Indeed, product sensitivity to variation is a key concept for rigid body assembly and has to be taken into account even when robot motions are planned. In the next Section such topic is investigated and an algorithm tackling it is presented.

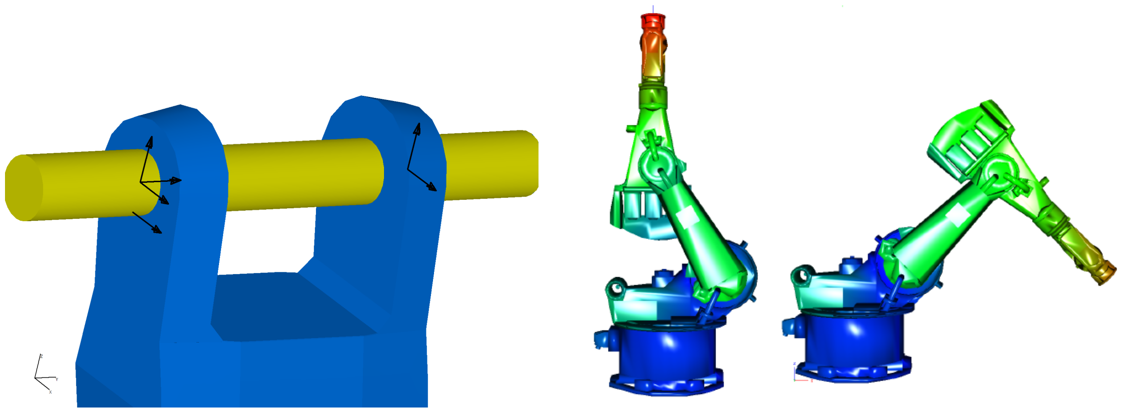
4.3 Non-nominal robot path planning

RQ4: How can geometrical variation be considered during collision free robot path planning?

The main idea to improve robustness in the robotic assembly operation is to enable robots to avoid motions in areas with high variation, preferring instead low variation zones. This idea is detailed into an algorithm presented in Paper 4. The method is able to deal with the geometrical variation due to the different robot kinematic configurations and variation for the products to be assembled. In Figure 4.3a a possible locating scheme for a revolute joint is illustrated. In Figure 4.3b geometrical sensitivity is evaluated for an industrial robot at two different configurations. The blue areas are the ones with less variation, the green ones are intermediate, whereas the red zones are the ones with most variation.

Computing variation in the robot workspace might be a computationally expensive task and variation data might be unavailable in the entire space, therefore three different ways to estimate it are also proposed. The ground idea is to modify distance in the BVHs in a way that accounts for geometrical variation of the included primitives such as triangles. Therefore, the method is automatic and quite fast for not very cluttered scenarios.

A difficult industrial test case is used to verify the method and an initial collision free robot motion is modified in order to decrease the probability of collision due to high variation areas.



(a) Locating scheme for a robot revolute joint

(b) Variation propagation for an industrial robot at two different configurations.

Figure 4.3: Modeling robot joint and evaluating variation

For details about it, please refer to Paper 4.

4.4 Validation and evaluation

In this Section a brief summary of how the research questions have been answered is presented, highlighting their evaluation on the application and the success criteria outlined in Section 1.3.

RQ1 has been answered in Paper 1. A decoupled method has been proposed: the first part solving exactly small instances (4 robots, about 30 tasks) and the second part proposing a novel transformation to avoid conflicts. They have been validated on instances adapted from literature problems related to TSP, namely the TSPLIB, (Reinelt 1991). Moreover, they have been validated on instances adapted from the industry, by comparing them to previous methods. Both algorithms solve the intended problems. Anyway, while the first method can be used to solve small bottleneck stations exactly, the second method needs more extensive evaluation regarding solution quality.

RQ2 has been answered in Paper 2. An efficient algorithm has been devised to exactly and efficiently solve small to large instances. The algorithm presented has been validated on random and industrial cases and compared to an existing solver, dominating its performance. This shows that it can be used in the intended situations and fulfills the success criteria of creating high quality solutions. Consequently, being part of a larger used method, it can even be of large benefit for the end user.

RQ3 has been answered in Paper 3. The algorithm is able to identify the possible subassemblies, both from the geometrical feasibility point of view and respecting the constraints imposed by the locators. Moreover, every assembly sequence can be given a quality measure and a global assembly sequence can be optimized. The corresponding tool has been validated on an public benchmark and on an industrial case. In some cases, manual work is still needed when the input is not perfect and therefore requires some enhancement to be fully industrially successful.

RQ4 has been answered in Paper 4. The method is able to deal with the geometrical variation due to the different robot kinematic configurations and variation for the products to be assembled. It has been successfully validated and tested on a difficult industrial case. Anyway, due to its high computational times, it remains to be further evaluated. In any case, it triggered industry to start using similar approaches exploiting the same idea in the commercial software IPS.

Chapter 5

Conclusions and future work

5.1 Conclusions

This thesis has been motivated by the research challenges and industrial need to improve robotic assembly planning by considering operations feasibility, robustness and equipment utilization. In fact, their corresponding research areas, respectively path planning, geometry assurance and sequencing optimization have been further developed and integrated and thereby enable better process performance.

Methods, algorithms and automatic tools to fulfill these goals have been implemented. They can even support both early decision making and detailed generation of assembly and robot motions for production environment.

Sequencing of operations has been optimized with respect to geometrical feasibility and cycle time for assembly products. It has been shown that some problems may be solved to optimality for small to medium size instances, whereas large sized ones require heuristic algorithms to get solutions of high quality. Assembly robustness has also been tackled for robot operations.

The focus has been on modeling, devising new algorithms, or improving computational performance for existing problems, therefore working at a detailed level. At the same time, providing automatic tools enabling new functionalities and integrating existing ones, thus working broader, has also been a driving force.

Shifting feasibility checks by means of these automatic tools toward earlier phases of product design and production preparation is undoubtedly a principal enabler for better quality, lower costs, and shorter ramp up times.

5.2 Future work

Of course, many new research ideas arise when solving problems and being in close collaboration with industry.

- **Compliant assembly sequence optimization**: in sheet metal assembly, welding points become inaccessible if parts are assembled in the wrong order and, furthermore, welding sequence affects the final product quality. A method to optimize assembly sequence accounting for both geometrical quality and cycle time is therefore highly valuable. Some preliminary results are presented in (Johan S. Carlson et al. 2014).

- **Choice of tools and robots**: robot assembly could even benefit of further optimization methods such as checking for different tools and robots performing assembly operations. Indeed, given a predefined set of tasks and CAD models, the first decision process for the layout engineer and the purchase department is to analyze what kind of tools, e.g. welding guns, and robots are needed. The size of the robots and tools, in fact, is not only decided based on the tool weight and workspace analysis, but can even be based on tasks feasibility issues from a geometrical perspective.

- **Robot placement**: placing a robot in a cell can affect cycle time substantially. The results for the one robot case in (Spensieri et al. 2016) can be generalized to several robots and more efficient algorithms are needed to support the layout engineer for large instances.

- **Generalization to different applications**: many considerations highlighted easily generalize to other process than assembly:
  - inspection applications performed by Coordinate Measuring Machines (CMMs) and robots;
  - additive manufacturing applications performed by robots consisting of complex motions with speed constraints;
  - many tasks still require human involvement due to their manual sensitivity and visual capabilities at the same time. Future work can investigate how different tasks can be dedicated to robots, to humans or even to a human-robot collaboration.

- **Exact algorithms for bottleneck stations**: to support challenging stations in the automotive lines, exact algorithms can resolve these cycle time bottlenecks enabling increased production when needed.

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