Thesis for the degree of Doctor of Philosophy

Computational Methods for Design, Planning and Verification regarding Deformable 1D Objects

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Cover image:
Three examples of a deformable 1D object modeled as a rod (*center*): an industrial robot with a dress pack (*top*), an electrical cable (*left*) and a cooler hose (*right*). The geometries are courtesy of Volvo Cars.

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to my family

Abstract

The industry of today is focused on using virtual tools in the realization of a new product. As late changes in a design and planning concept can be extremely costly, there are many benefits to discovering and addressing problems as early as possible: fewer iterations between the different product realization phases and shorter lead-times, reduced numbers of physical prototypes and test series, fewer on-line adjustments in the production system and, in the end, a product of a higher quality.

A topic of special interest is *design*, *planning* and *verification* regarding *deformable 1D objects*, such as electrical cables, wiring harnesses, hoses, pipes and tubes. These objects are geometrically characterized as *one-dimensional* (1D) in the sense that one dimension is significantly larger than the other two. Therefore, they usually exhibit large *deformations* when subject to external forces and moments, which may cause quality problems and unexpected geometrical interference between objects both in production and during the life-span of a product. Hence, it is of great industrial impact if problems with deformation can be addressed early in the virtual product realization process.

This thesis presents five computational methods for design, planning and verification regarding deformable 1D objects. The first two methods are targeted at *routing design* (i.e. automatically finding a reference design and a routed configuration): one method for objects such as cables that may be significantly deformed due to gravity in their routed configurations and another method for preformed hoses that are *not* significantly deformed. The third method is in fact a methodology for performing *variation analysis* that in particular includes a method for generating tolerance envelopes. The fourth method is aimed at *assembly verification* (i.e determining whether or not the object can be installed into its routed configuration), whereas the fifth method is aimed at *production planning* by performing path optimization for an industrial robot with a deformable dress pack. In summary, the methods allow for automatically finding a routed design, verifying the routed design with respect to both geometrical variation and assembly and improving operations in production with respect to deformation.

The main research challenge in developing the methods is to combine simulation of deformable 1D objects with iterative algorithms for path planning, variation simulation and optimization. For this purpose, a discrete Cosserat rod model is used to enable efficient and accurate computations of large deformations.

Keywords: simulation of deformable 1D objects, routing design, variation analysis, assembly verification, production planning, path planning, non-linear optimization.

Acknowledgments

This study has been carried out at the Department of Industrial and Material Science (IMS) at Chalmers University of Technology and at the Fraunhofer-Chalmers Centre (FCC) in Gothenburg, Sweden.

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Tomas Hermansson
Gothenburg, February 2021

List of publications

This thesis is based on the following appended papers:

Paper A. **T. Hermansson**, R. Bohlin, J. S. Carlson and R. Söderberg. *Automatic routing of flexible 1D components with functional and manufacturing constraints.* Journal of Computer-Aided Design Vol. 79. pp. 27-35, 2016.

Paper B. **T. Hermansson**, E. Åblad. *Automatic routing of preformed hoses.* Journal of Computer-Aided Design, 2020 (*submitted for publication*).

Paper C. **T. Hermansson**, J. S. Carlson, S. Björkenstam and R. Söderberg. *Geometric variation simulation and robust design for flexible cables and hoses.* Journal of engineering manufacture Vol. 227, pp. 681-689, 2013.

Paper D. **T. Hermansson**, R. Bohlin, J. S. Carlson and R. Söderberg. *Automatic assembly path planning for wiring harness installations.* Journal of Manufacturing Systems Vol. 32. pp. 417-422, 2013.

Paper E. **T. Hermansson**, J. S. Carlson, J. Linn and J. Kressin. *Quasi-static path optimization for industrial robots with dress packs.* Journal of Robotics and Computer-Integrated Manufacturing Vol. 68, 2021.

Other relevant publications:

J. Linn, **T. Hermansson**, F. Andersson and F. Schneider. *Kinetic aspects of discrete Cosserat rods.* Proceedings of the 8th ECCOMAS Thematic Conference on Multibody Dynamics, 2017, Prague, Czech Republic.

V. Dörlich, **T. Hermansson** and J. Linn. *Localized helix configurations of discrete Cosserat rods.* Proceedings of the 9th ECCOMAS Thematic Conference on Multibody Dynamics Vol. 53, pp. 191-198, 2019, Duisburg, Germany.

F. Schneider, J. Linn, **T. Hermansson** and F. Andersson. *Cable dynamics and fatigue analysis for digital mock-up in vehicle industry.* Proceedings of the 8th ECCOMAS Thematic Conference on Multibody Dynamics, 2017, Prague, Czech Republic.

T. Hermansson, S. Vajedi, T. Forsberg, F. Ekstedt, J. Kressin, C. Toft and J. S. Carlson. *Identification of material parameters of complex cables from scanned 3D shapes.* Procedia CIRP Vol. 43. pp. 280-285, 2016, Gothenburg, Sweden.

Distribution of work

The work on the appended papers was distributed as follows:

Paper A. Hermansson and Bohlin outlined the concept of the method. Hermansson implemented the routing and refinement algorithms and performed the case study. Hermansson drafted the paper, while the other authors contributed continuously with comments and feedback.

Paper B. Hermansson and Åblad outlined the concept of the method. Åblad and Hermansson implemented the routing algorithm and Hermansson performed the case studies. Hermansson drafted most of the paper, whereas Åblad drafted Section 2.5. Åblad contributed continuously with comments and feedback.

Paper C. Hermansson, Carlson and Björkenstam outlined the concept, which is an extension of the virtual variation analysis framework first introduced by Söderberg towards deformable 1D objects. Hermansson implemented the variation analysis framework, whereas Björkenstam implemented the tolerance envelope generation algorithm. Hermansson drafted most of the paper, whereas Carlson drafted the introduction. All co-authors contributed continuously with comments and feedback.

Paper D. Hermansson and Bohlin outlined the concept of the method. Hermansson implemented the algorithm and performed the case study. Hermansson drafted the paper, while the other authors contributed continuously with comments and feedback.

Paper E. Hermansson outlined the concept of the method. Hermansson implemented the path optimization algorithm and performed the case study. The stud welding station used in the case study was prepared by Kressin. Hermansson drafted the paper, while the other authors contributed continuously with comments and feedback.

The simulation model for deformable 1D objects used in all papers was developed by Hermansson, Holger Lang and Joachim Linn et al. at Fraunhofer-ITWM and was implemented by Hermansson.

Contents

Part I

Introductory chapters

Chapter 1

Introduction

This chapter is an introduction to the research presented in this thesis and provides research scope, research approach and a brief outline.

1.1 Background

The development of a new product from an existing idea to market introduction can be described by the *product realization process* (Figure 1.1). In the *design phase*, a new product design is developed based on different aesthetical and functional requirements. In the *planning phase*, a process for manufacturing and assembly of the suggested design is planned by generating a detailed set of tasks and instructions for humans and/or machines. Together, the design and planning phases form the *concept phase*. Next, in the *verification phase*, the concept is verified using physical prototypes and test series. Finally, in the *production phase*, the full production starts. The process is monitored in order to identify and address problems with the product and the process and to collect data and transfer knowledge to future product development.

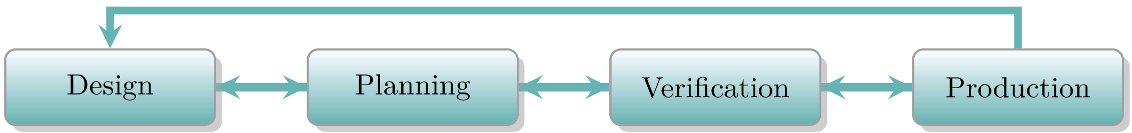


Figure 1.1: The product realization process.

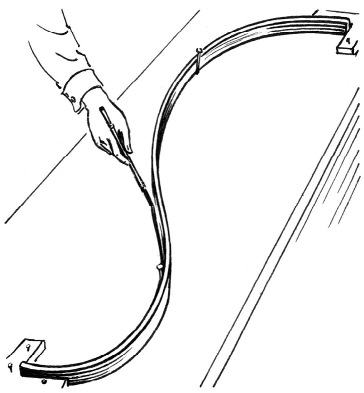
1.1.1 Virtual product realization

Quality problems are often discovered during the verification and production phases. A change in a design or planning concept at this stage can be extremely costly, as new physical prototypes need to be created and production needs to be re-tested. In the worst possible scenario, this can lead to market delays and bad publicity. Therefore, the industry of today is focused on using virtual tools to develop a concept and verify it as early as possible. For example, *computer-aided design* (CAD) tools are used for rendering the design of the product, *computer-aided tolerancing* (CAT) tools are used for verifying and controlling the effect of geometrical variation, *path planning and sequencing* tools are used for planning the assembly process and *product lifecycle management* (PLM) tools are used for documenting the process. The benefits are many from both a financial and sustainability perspective; fewer iterations between the different phases and shorter lead-times, a less demanding verification phase with a reduced number of physical prototypes and test series, fewer on-line adjustments in the production system and, in the end, a product of a higher quality.

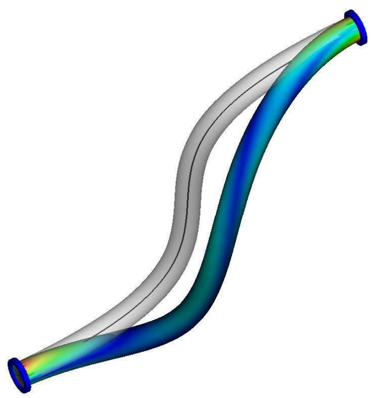
1.1.2 Challenges with deformation

A challenge in using virtual tools arises when the product or the production system consists of objects that are *deformed* elastically when subject to external forces and moments. Deformation can cause quality problems and unexpected geometrical interference between objects both in the production phase and during the life-span of the product. In fact, late online adjustments and product failures are often attributed to deformable objects (Ng et al. 2000; Falck et al. 2008). Traditionally, these problems are detected when performing measurements on physical prototypes and when running test series.

In the early design phase, the design engineer needs to either assume that an object will not be significantly deformed from its reference design or make a qualified guess of how an object will deform. In CAD tools, deformable objects are typically represented with mathematical surfaces or curves. For example, the *spline* is a smooth, piecewise polynomial space curve defined by a set of control points. Interestingly, a spline was originally a strip of wood used in ship building (Farin 2002) to design smooth, energy-minimal curves (see Figure 1.2a). There is, however, no reason to believe that these models are physically accurate representations of deformable objects in general and in the presence of gravity (see Figure 1.2b). Therefore, *virtual simulation tools* are used to verify a concept when deformation is involved.



(a) A flat spline configuration.



(b) Simulation of a rubber hose with and without gravity.

Figure 1.2

1.1.3 Deformable 1D objects

Of special interest are *deformable 1D objects* such as electrical cables, wiring harnesses, hoses, pipes and tubes. In a complex product or production system, these objects appear in a variety of applications, e.g. wired data communication, energy transfer (electrical power supply and hydraulics) and heating and cooling systems. These objects are geometrically characterized as *one-dimensional* (1D) in the sense that one dimension is significantly larger than the other two. Therefore, they usually exhibit large deformations when subject to external forces and moments, which may be very problematic. For example, as the automotive industry of today is focusing on electrified and hybrid solutions, both conventional combustion engines and battery supplied electrical engines need to take their place in an already limited design space (see Figure 1.3). Late design changes in order to avoid quality problems can therefore result in solutions involving concealed routings and tricky assembly operations for all cables and hoses involved. As another example, industrial robots in the production system are often externally dressed with electrical cables and supply hoses in what is referred to as the *robot dress pack*. Problems with robot dress packs are a major reason for late on-line adjustments and robot station down-time at Volvo Cars (Eriksson 2005b; Eriksson 2005a).

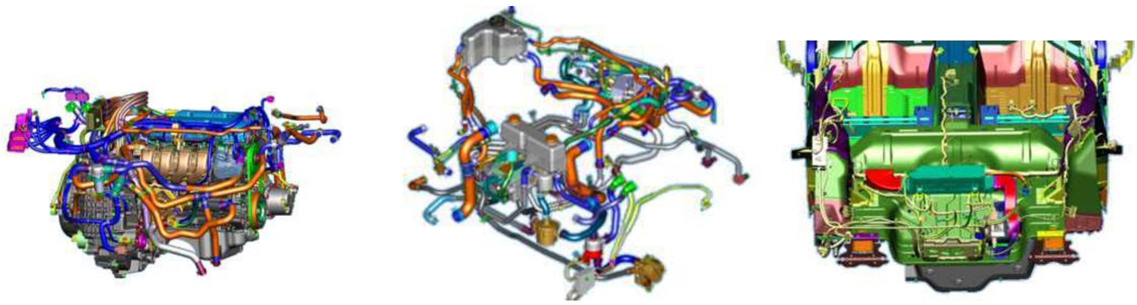


Figure 1.3: Cooling systems for a traditional engine, an electrical engine and a battery.

Today, virtual simulation tools can be used to *manually* analyze and verify a given concept, e.g. how the reference design and the placement of connection points influence the deformation. However, there is still a research challenge in combining simulation with *automatic* methods for *design*, *planning* and *verification*. For example, how can an object be routed so that excessive design length is minimized without violating geometrical design constraints? How does geometrical variation in design length or positions of the connection points influence the deformation of an object? Can an object be installed into its routed configuration? Can an operation in the production system be improved with respect to deformation? *It is of great industrial impact if these questions can be answered using computational methods early in the virtual product realization process.*

1.2 Research scope

This thesis aims to investigate how simulation of deformable 1D objects in a product and/or a production system can be combined with computational methods for design, planning and verification to further strengthen the virtual product realization process. The main focus is to develop and implement new methods for the following processes:

Routing design Routing a deformable 1D object is the process of finding a reference design and a collision-free routed configuration of the object that joins a given set of connection points. Usually, a short reference design length is desired and often a set of geometrical design constraints (e.g. a minimum allowed bending radius) need to be satisfied to allow for the manufacturing of the object and/or for the object to function properly.

Variation analysis The routed design of a deformable 1D object is verified with respect to robustness. Geometrical variation from manufacturing and assembly processes propagates to deviation from the nominal design in the final product. For deformable 1D objects, geometrical variation in, for example, reference design length, positions of connection points and even material properties may cause large deformations and needs to be analyzed using variation simulation tools.

Assembly verification The routed design of a deformable 1D object is verified with respect to assembly to ensure that there exists a feasible assembly operation. For example, routed configurations of wiring harnesses can be very concealed and consist of several branches, break-outs and connectors. It needs to be verified that a harness can be installed into its routed configuration, e.g. starting from a 2D build-board layout, without stretching or bending the harness more than necessary.

Production planning Paths for executing operations in production such as assembly and welding are either created manually or generated automatically with path planning and sequencing tools. Manually finding a collision-free path with respect to deformable 1D objects using a virtual simulation tool can be very challenging and path planning tools do not usually consider deformations in the product and/or production system. Therefore, planned paths may need to be adjusted and improved with respect to deformation.

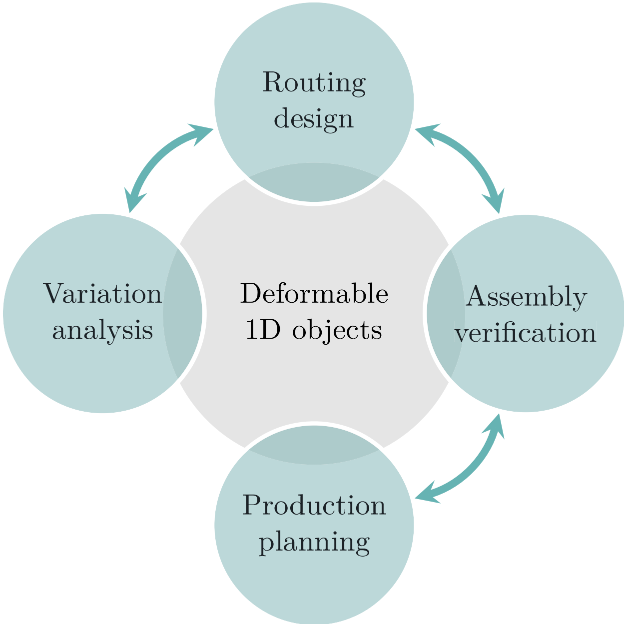


Figure 1.4: Design, planning and verification regarding deformable 1D objects.

1.2.1 Research questions

The research scope is defined by four research questions. Each research question shall be answered by developing one or several methods for the corresponding process in Figure 1.4 satisfying a set of method requirements.

> **RQ1** How can a deformable 1D object be automatically routed in a collision-free way with respect to geometrical design constraints? (*routing design*)

This research question shall be answered by developing one or several routing methods that propose a reference design and a collision-free routed configuration of a deformable 1D object in static equilibrium satisfying a set of geometrical design constraints. The reference design shall be of minimum length without stretching or bending the object more than necessary and there shall be sufficient clearance between the routed configuration and the surrounding geometry. The choice of routing method might depend on the type of object; electrical cables are usually connected in a wiring harness structure and exhibit large deformations, whereas hoses and pipes can have a preformed reference design that reduces the amount of deformation.

> **RQ2** How can the routed design of a deformable 1D object be analyzed with respect to geometrical variation? (*variation analysis*)

This research question shall be answered by developing a methodology for analyzing and visualizing the effect of geometrical variation for a deformable 1D object in its routed configuration with respect to a given set of design parameter tolerances. Design parameters are typically reference design length and positions of the connection points. Of special interest is a method for generating the design space volume possibly occupied by an object subject to geometrical variation. This is a worst case volume that can also be useful for design and placement of other objects.

> **RQ3** How can it be verified that the routed design of a deformable 1D object is feasible with respect to assembly? (*assembly verification*)

This research question shall be answered by developing a method for verifying whether it is possible to manipulate a deformable 1D object from an initial configuration to its routed configuration by moving its connection points and without stretching or bending the object more than necessary. If it is possible, then the method shall output a feasible assembly manipulation to provide an early indication on how to plan the assembly operation.

> **RQ4** How can a planned path be optimized with respect to deformable 1D objects in the product and/or production system? (*production planning*)

This research question shall be answered by developing a method that modifies an existing path such that deformable 1D objects in the product and/or production system are collision-free and are not stretched or bent more than necessary during their motions. It can be assumed that all rigid parts are collision-free during the initial motion and that all deformable 1D objects are routed in a collision-free way when the motion starts.

1.2.2 Success criteria

The ultimate *success criterion* for evaluating the research results is that all research questions are answered by developing methods that are consistent with the method requirements. To determine whether or not the methods meet the industrial and scientific demands within the research project, a set of *measurable success criteria* are defined:

Compatibility The input and output of the methods shall be compatible with industrial standard data formats regarding geometrical representation and robot programs.

Accuracy The simulation model must accurately account for large non-linear deformations in static equilibrium and the collision detection must be correct with respect to the geometrical representation of the objects involved. The maximum allowed deviation between the simulation model and the real-world object is tied to the clearance requirements and is typically in the magnitude of 5-10 mm.

Speed The methods are to be used iteratively in the virtual product realization process. It is therefore important that running times are short and in the magnitude of *minutes* for typical industrial use cases on a standard desktop computer.

Contribution The methods developed shall make a significant contribution to their relevant research areas and be shared with the scientific community.

1.2.3 Delimitations

The research presented in this thesis is aimed at resolving problems related to deformation. Hence, the main focus is to help develop a concept and verify and improve it regarding deformation. Therefore, it is out of scope to consider simulation of the actual function of an object, e.g. ensuring that the electrical current in a power cable or the fluid flow inside a hose is consistent with functional requirements. Sometimes, however, functional requirements may be translated using rules of thumb into geometrical design constraints that need to be satisfied. For example, the bending radius of a hose or pipe must generally not be less than a minimum allowed value to avoid pressure drops.

Choice of simulation model

Delimitations and approximations naturally need to be made when deciding on a simulation model. The methods presented in this thesis are based on iterative algorithms and rely on having a simulation model that enables *efficient* and *accurate* computations of large deformations of 1D objects. A reasonable trade-off is using a rod representation that exploits the object's one-dimensional structure and assuming that only conservative forces are involved (see Section 2.1). Under these assumptions, detailed simulation of for example friction, contact interaction between strands in the material and hysteresis is not possible. Furthermore, it is assumed that all deformations correspond to *static equilibrium* of forces and moments, i.e. inertial effects are not considered as they are not relevant in the early design and verification phases. It is also not desired in the planning phase to generate paths that rely on dynamics in order to avoid contact with other objects.

1.3 Research approach

In choosing a proper research approach, a high-level distinction can first be made between *basic research* and *applied research* (Williamson 2002). Basic research is directed at developing a theory and advances the general knowledge in society, whereas applied research targets a specific problem and develops methods with which to understand and improve the situation. With a scope of developing computational methods for design, planning and verification, the research presented in this thesis naturally falls into the latter category.

Being applied research, the research work is conducted in a series of research projects initiated by both industry and government in the spirit of the Wingquist Laboratory philosophy and the results are implemented in IPS, which is a software suite for virtual product realization. This platform helps to define and clarify the research scope in terms of industrial demand and encourages the research results to be both transferable to an industrial setting and shared with the scientific community.

1.3.1 Research methodology

A research methodology describes how to systematically structure the work in a research project to ensure that the research questions are properly formulated and successfully answered. The research presented in this thesis is related to product design. The *Design Research Methodology* (DRM) is a framework proposed by Blessing et al. (2009) with a strong tradition in production and product development and divides design research into four stages (Figure 1.5). Iterations between the different stages are highly encouraged in order to reach a set of methods and tools that meet the success criteria.

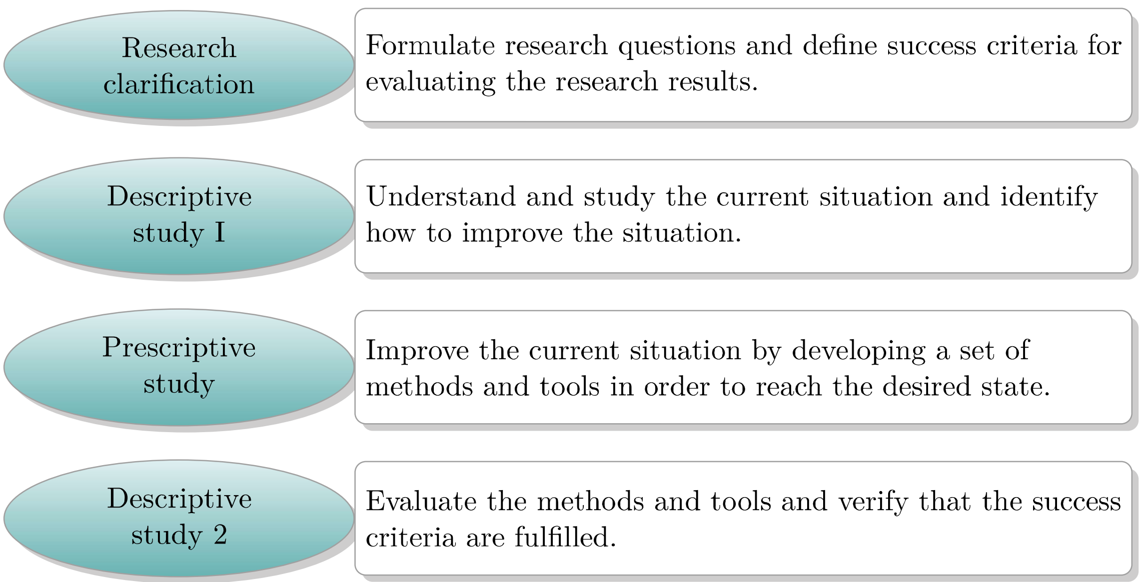


Figure 1.5: The four stages of DRM.

The research in this thesis is guided by the DRM framework. The four research questions in Section 1.2.1 are independent and can be answered within each corresponding research project. Divided into the four DRM stages, the research work is structured in each research project as follows:

Research clarification Based on demand and requests from partners in the research project, a research question is formulated. The expected research result from answering the research question is a method for the corresponding process within virtual product realization. In order to formulate the research question and method requirements, a preliminary survey of available methods is performed and relevant research areas are identified. A set of success criteria (see Section 1.2.2) are defined to ensure that the method meets both industrial and scientific demands.

Descriptive study I A literature review is made in order to position the research question within each identified research area and to identify any knowledge gaps. Existing methods and simulation models are then evaluated with respect to the success criteria. Based on the evaluation, it is decided what types of method and simulation model need to be developed. If the choice of method has implications on limitations or approximations, then it is important that this is performed in iteration with the partners in the research project.

Prescriptive study The method and simulation model (if needed) are developed and implemented. In an algorithm design process, the method is checked for correctness with respect to its requirements and the results are validated. In the spirit of the Wingquist Laboratory implementation strategy, the method is implemented in a demonstrator version of the IPS software in order to facilitate systematic testing and evaluation in an industrial setting.

Descriptive study II The results are evaluated based on a set of academic benchmark cases and industrial use cases and feedback from industrial partners in the research project. If the success criteria are not met, then the method development continues. If necessary, the method requirements might be revised or new delimitations or approximations need to be introduced.

1.3.2 Validation and verification

Validation and verification are important activities in order to make sure that the research questions and success criteria are properly formulated and to ensure the quality of the research results. The terms "validation" and "verification" are sometimes used interchangeably depending on research area or application. In this thesis, the following interpretation is used:

> Validation answers the question "Did we do the right thing?" and verification answers the question "Did we do it the right way?".

In terms of the research scope (Section 1.2), validation is the assessment that the simulation model accurately accounts for the deformation of the real-world object and that the methods developed actually solve the real-world problems. The simulation model can be validated by comparison with measurements and the methods can be validated by solving industrial use cases in the research projects and by being adopted and used by industrial companies. Verification, on the other hand, is the assessment that the methods and simulation model are consistent with existing theory. *Verification by acceptance* is one approach, in which the scientific contribution is verified by being accepted for publication after having undergone a peer-review process with experts in relevant research areas.

1.4 Thesis outline

The thesis is structured as follows:

Chapter 1 is an introduction to the research presented in this thesis and provides research scope, research approach and a brief outline.

Chapter 2 provides a theoretical background for the research presented in this thesis with an overview of simulation of deformable 1D objects, path planning and geometry assurance.

Chapter 3 provides a short summary of the methods developed and the corresponding results from the papers appended to this thesis.

Chapter 4 discusses the research results in relation to the research questions, validation and verification and its scientific and industrial contribution.

Chapter 5 concludes the research presented in this thesis and provides an outlook for future work.

Chapter 2

Frame of reference

> This chapter provides a theoretical background for the research presented in this thesis with an overview of simulation of deformable 1D objects, path planning and geometry assurance.

2.1 Simulation of deformable 1D objects

The methods presented in this thesis rely on having a simulation model that enables efficient and accurate computations of large deformations of 1D objects in static equilibrium. For these purposes, the *Cosserat rod* is the preferred model of choice. This section provides a short introduction to the field of continuum mechanics and a derivation of a discrete Cosserat rod model.

2.1.1 Continuum mechanics

The theory of continuum mechanics provides a wide selection of physical models with which to simulate deformations of solid objects (Gurtin 1981). The main ingredients of any continuum-mechanical model are *kinematics*, *constitutive laws* and *equilibrium equations*. The kinematics describe the inherent geometrical structure of the object. The local change of shape of an object is measured in terms of strains which are related to internal stresses via a constitutive law. Equilibrium equations can be derived from variational principles and ensure that the external forces acting on the object and inertial forces are in equilibrium with the internal ones encoded in the stresses. In particular, static equilibrium occurs when an object is at rest, i.e. the inertial forces are zero.

2.1.2 Statics

Assume that a deformable object undergoes a small virtual deformation that is compatible with its kinematics. The *principle of virtual work* then states that the object is in static equilibrium when the virtual external work $\delta W^{(ext)}$ done by forces acting on the object and the virtual internal work $\delta W^{(int)}$ in the object add up to zero,

$$\delta W^{(int)} + \delta W^{(ext)} = 0. \tag{2.1}$$

If all forces involved are *conservative*, there exists a *total potential energy* function V and (2.1) is equivalent to

$$\delta V = 0. \tag{2.2}$$

This special case is known as the *principle of minimum potential energy* which states that a configuration of the object in static equilibrium is a stationary point to the total potential energy.

Lagrangian statics

Within the framework of *constrained Lagrangian mechanics*, configurations in static equilibrium can be characterized as follows: Formally, let $Q \subseteq \mathbb{R}^n$ be a (finite-dimensional) set of possible configurations of the object and let $V \in C^1(Q;\mathbb{R})$ be a total potential energy function measuring the work done by conservative forces. Furthermore, let the object be subject to a set of holonomic constraints described by the constraint function $\boldsymbol{g} \in C^1(Q;\mathbb{R}^m)$ such that $\boldsymbol{g}(\boldsymbol{q}) = \mathbf{0}^m$ must hold for any feasible configuration $\boldsymbol{q} \in Q$ and where $\mathbf{0}^k$ is shorthand notation for $\mathbf{0} \in \mathbb{R}^k$. The constraints typically encode boundary conditions or other kinematic constraints imposed on the object. By necessity, all stationary points to the potential energy function must then satisfy the *Euler-Lagrange equations*

$$\frac{\partial V}{\partial \boldsymbol{q}}(\boldsymbol{q}) + \boldsymbol{\lambda} \cdot \frac{\partial \boldsymbol{g}}{\partial \boldsymbol{q}}(\boldsymbol{q}) = \mathbf{0}^n, \tag{2.3a}$$

$$\boldsymbol{g}(\boldsymbol{q}) = \mathbf{0}^m, \tag{2.3b}$$

where $\boldsymbol{\lambda} \in \mathbb{R}^m$ are the constraint multipliers. Note that the principle of minimum potential energy only requires a point to be stationary. In addition, a configuration in static equilibrium is *stable* if it (locally) minimizes the total potential energy function subject to the constraints, i.e. it is a solution to the *potential energy minimization problem*

$$\begin{aligned} \text{Minimize } & V(\boldsymbol{q}) \\ \text{subject to } & \boldsymbol{g}(\boldsymbol{q}) = \mathbf{0}^m, \\ & \boldsymbol{q} \in Q. \end{aligned} \tag{2.4}$$

Besides finding stable configurations, solving (2.4) has the benefit that any algorithm for non-linear programming can be used without the explicit administration of constraint multipliers. On the other hand, an advantage of solving the Euler-Lagrange equations (2.3) is that generalized non-conservative forces can be added to the right-hand side of (2.3a) according to d'Alembert's principle in generalized coordinates.

Numerical solutions

In order to numerically obtain a configuration in static equilibrium, the Euler-Lagrange equations (2.3) or the potential energy minimization problem (2.4) need to be solved over a finite-dimensional set of configurations Q. Hence for a continuum object, a discrete representation, dividing the object into a finite number of elements, is needed. In *finite element analysis*, the object configuration is approximated as a linear combination of shape functions and a weak formulation of the static equilibrium equations is solved (Geradin et al. 2001). For small deformations, linear expressions for the strain measures in terms of displacements from the reference configuration may be used, yielding a linear system of equations to be solved. Large non-linear deformations can be accounted for with, for example, co-rotational finite elements (Nour-Omid et al. 1991) or by re-parametrization of the weak formulation (Betsch et al. 2002).

2.1.3 Cosserat rods

This thesis considers 1D objects, i.e. objects with a one-dimensional structure in the sense that one dimension (the length) is significantly larger than the other two (the cross-sectional plane), that deform elastically when subject to external forces and moments. In the field of continuum mechanics, large deformations of such fiber-like objects can be properly modeled using geometrically exact *Cosserat rods*. The Cosserat rod can be seen as the non-linear generalization of the *Timoshenko beam*. For a thorough introduction to Cosserat rod theory, the reader is referred to Antman (2005) and the seminal work by Reissner (1973) and Simo (1985).

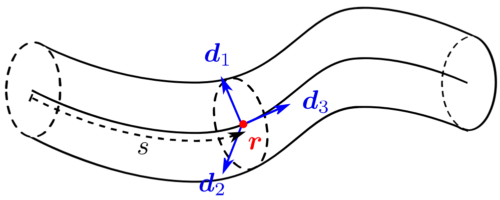


Figure 2.1: A rod configuration.

Kinematics

The basic kinematic assumption of the Cosserat rod model is that, although deformations of the rod can correspond to large (finite) rotations and translations in space, the strains remain small and hence, the local cross-sectional plane is not significantly deformed. The configuration of a Cosserat rod of undeformed length L is then determined by a *framed curve*: a space curve $\boldsymbol{r}$ representing its centerline and an orthonormal frame of directors $\boldsymbol{R} = (\boldsymbol{d}_1, \boldsymbol{d}_2, \boldsymbol{d}_3) \in \mathrm{SO}(3)$ defining the orientation of the cross-sectional plane along the centerline,

$$s \mapsto (\boldsymbol{r}(s), \boldsymbol{R}(s)) \in \mathbb{R}^3 \times \mathrm{SO}(3), \tag{2.5}$$

where $s \in [0, L]$ is the arc length parameter along the undeformed centerline and $\mathrm{SO}(3)$ is the space of spatial rotations in $\mathbb{R}^3$.

Strain measures

The kinematics of framed curves determine the possible deformation modes of a Cosserat rod. These are *bending* around a direction in the cross-sectional plane spanned by $\boldsymbol{d}_1$ and $\boldsymbol{d}_2$, *torsion/twisting* around the cross section normal $\boldsymbol{d}_3$, *stretching* in the $\boldsymbol{d}_3$ direction and *shearing*, i.e. tilting of the cross section normal $\boldsymbol{d}_3$ with respect to the curve tangent $\frac{d\boldsymbol{r}}{ds}$. The spatial deformation of the rod is mainly governed by bending and torsion meanwhile the amount of stretching and shearing is very small but non-zero.[1]

For a given rod configuration, differential invariant *strain measures* can be defined with respect to the director frame. The shearing/stretching strain vector $\boldsymbol{\Gamma} = (\Gamma_1, \Gamma_2, \Gamma_3)^T$ is

$$\boldsymbol{\Gamma} = \boldsymbol{R}^T \cdot \frac{d\boldsymbol{r}}{ds} - \boldsymbol{e}_3, \tag{2.6a}$$

where $\boldsymbol{e}_3$ is the standard basis vector in the z direction. Γ_1 and Γ_2 represent the transverse shearing strain components and Γ_3 represents the tension strain. The bending/torsion strain vector $\boldsymbol{\Omega} = (\Omega_1, \Omega_2, \Omega_3)^T$ is defined by the skew-symmetric tensor

$$\hat{\boldsymbol{\Omega}} = \boldsymbol{R}^T \cdot \frac{d\boldsymbol{R}}{ds}. \tag{2.6b}$$

Ω_1 and Ω_2 represent the bending strain components and Ω_3 represents the torsion strain.

Total potential energy

With a linear-elastic constitutive law (which can be justified by the kinematic assumption of strains locally being small), the *stored strain energy densities* are quadratic forms in the corresponding strain measures (2.6),

$$\mathcal{V}_\Gamma = \frac{1}{2}(\boldsymbol{\Gamma} - \boldsymbol{\Gamma}_0) \cdot \boldsymbol{K}_\Gamma \cdot (\boldsymbol{\Gamma} - \boldsymbol{\Gamma}_0), \tag{2.7a}$$

$$\mathcal{V}_\Omega = \frac{1}{2}(\boldsymbol{\Omega} - \boldsymbol{\Omega}_0) \cdot \boldsymbol{K}_\Omega \cdot (\boldsymbol{\Omega} - \boldsymbol{\Omega}_0), \tag{2.7b}$$

for known effective stiffness tensors $\boldsymbol{K}_\Gamma$ and $\boldsymbol{K}_\Omega$ and reference configuration strains $\boldsymbol{\Gamma}_0$ and $\boldsymbol{\Omega}_0$. Furthermore, the potential energy density due to gravity is

$$\mathcal{V}_\rho = -\rho \boldsymbol{g} \cdot \boldsymbol{r}, \tag{2.7c}$$

for known length density ρ and where $\boldsymbol{g}$ is the gravitational field constant. Conservative *contact forces* with the surrounding geometry are modeled according to the potential energy density

$$\mathcal{V}_\Phi = k_\Phi \delta(\boldsymbol{r})^{\frac{5}{2}}, \tag{2.7d}$$

[1] In the special case of an *inextensible Kirchhoff rod*, shearing and stretching is explicitly discarded by imposing the kinematic constraints that the curve tangent is always of unit length and aligned with the cross-sectional plane normal (i.e. $\boldsymbol{d}_3 = \frac{d\boldsymbol{r}}{ds}$). As such, the Kirchhoff rod can be seen as the non-linear generalization of the *Euler-Bernoulli beam*.

where k_Φ is an elastic stiffness parameter and δ is the penetration depth between the rod and the surrounding geometry at $\boldsymbol{r}$.

The total potential energy V is now obtained by integrating the energy densities (2.7) along the rod,

$$V = \int_{s=0}^{L} \mathcal{V}_\Gamma + \mathcal{V}_\Omega + \mathcal{V}_\rho + \mathcal{V}_\Phi \, ds. \tag{2.8}$$

2.1.4 Discrete Cosserat rods

In order to numerically obtain a configuration in static equilibrium (Section 2.1.2), a discrete representation of the rod model is required. Most open-source codes and commercial software packages for simulation of deformable objects are either focused on dynamic simulation (e.g. Bullet and Elastica), or on using high-order finite elements suitable for arbitrary complex structures (e.g. Abaqus and Adams) that usually involve sophisticated interpolation schemes. For the methods in this thesis, it is important that the simulation model is simple and computationally efficient to evaluate during the process of energy minimization. For these purposes, the discrete Cosserat rod model proposed by Lang et al. (2011) is used. This model, inspired by discrete differential geometry (Bobenko et al. 1999; Bergou et al. 2008), evaluates the strain measures using geometric finite differences and preserves essential properties of the non-linear continuum theory also for coarse discretizations (Linn et al. 2017).

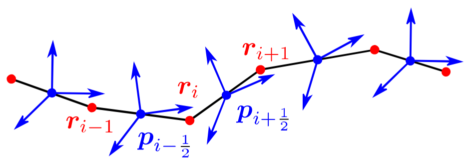


Figure 2.2: A discrete rod configuration.

Discretization

The rod is discretized on a *staggered grid* by first dividing the arc length interval $[0, L]$ into $N-1$ segments by N vertices $\{s_i\}_{i=1}^N$ such that $0 = s_1 < s_2 < \ldots < s_N = L$. Consequently, the segment midpoints are $s_{i+\frac{1}{2}} = \frac{1}{2}(s_i + s_{i+1})$, the segment arc lengths are $\Delta s_{i+\frac{1}{2}} = s_{i+1} - s_i$ and the arc lengths between adjacent midpoints are $\Delta s_i = \frac{1}{2}(s_{i+1} - s_{i-1})$. In a discrete rod configuration, the centerline variables are positions $\boldsymbol{r}_i \in \mathbb{R}^3$ associated with the vertices s_i, whereas the director frame variables are *quaternions* $\boldsymbol{p}_{i+\frac{1}{2}} \in \mathbb{H}$ associated with the midpoints $s_{i+\frac{1}{2}}$. Quaternions are elements that can be identified with four real numbers (i.e. $\mathbb{H} \cong \mathbb{R}^4$) and *unit quaternions* are a convenient representation of elements in SO(3). The midpoint quaternions $\boldsymbol{p}_{i+\frac{1}{2}}$ are thus projected onto the unit sphere S^3 by imposing the unit quaternion constraints

$$\|\boldsymbol{p}_{i+\frac{1}{2}}\|^2 - 1 = 0. \tag{2.9}$$

Boundary conditions

Boundary conditions holding the rod in place are naturally modeled as kinematic constraints. For example, the rod can be fixed in space at the vertex s_i to the position $\tilde{\boldsymbol{r}} \in \mathbb{R}^3$ with the position constraint

$$\boldsymbol{r}_i - \tilde{\boldsymbol{r}} = \mathbf{0}^3 \tag{2.10a}$$

and to the orientation represented by $\tilde{\boldsymbol{p}} \in \mathbb{H}$ with the orientation constraints

$$\log(\tilde{\boldsymbol{p}}) - \log(\boldsymbol{p}_{i\pm\frac{1}{2}}) = \mathbf{0}^3. \tag{2.10b}$$

Kinematic constraints can also be defined for modeling, for example, cable clips and branching points in systems of deformable 1D objects.

Discrete strain measures and total potential energy

For a given discrete rod configuration, the shearing/stretching strain vector is evaluated on the midpoints with a finite difference approximation of the centerline tangent as

$$\boldsymbol{\Gamma}_{i+\frac{1}{2}} = \boldsymbol{p}^*_{i+\frac{1}{2}} \circ \frac{\boldsymbol{r}_{i+1} - \boldsymbol{r}_i}{\Delta s_{i+\frac{1}{2}}} \circ \boldsymbol{p}_{i+\frac{1}{2}} - \boldsymbol{e}_3$$

and the bending/torsion strain vector is evaluated at the interior vertices as

$$\boldsymbol{\Omega}_i = \frac{2}{\Delta s_i} \log(\boldsymbol{p}^*_{i-\frac{1}{2}} \circ \boldsymbol{p}_{i+\frac{1}{2}}).$$

The total potential energy of the discrete rod in analogue to (2.8) is then numerically integrated to

$$\begin{aligned} V = &\sum_{i=1}^{N-1} \frac{1}{2}(\boldsymbol{\Gamma}_{i+\frac{1}{2}} - \boldsymbol{\Gamma}_{i+\frac{1}{2},0}) \cdot \boldsymbol{K}_\Gamma \cdot (\boldsymbol{\Gamma}_{i+\frac{1}{2}} - \boldsymbol{\Gamma}_{i+\frac{1}{2},0}) \Delta s_{i+\frac{1}{2}} \\ &+ \sum_{i=2}^{N-1} \frac{1}{2}(\boldsymbol{\Omega}_i - \boldsymbol{\Omega}_{i,0}) \cdot \boldsymbol{K}_\Omega \cdot (\boldsymbol{\Omega}_i - \boldsymbol{\Omega}_{i,0}) \Delta s_i + \sum_{i=1}^{N} k_\Phi \delta(\boldsymbol{r}_i)^{\frac{5}{2}} - \rho \boldsymbol{g} \cdot \boldsymbol{r}_i \, \Delta s_i. \end{aligned} \tag{2.11}$$

A discrete rod configuration in static equilibrium can now be computed by minimizing the total potential energy V of the discrete rod (2.11) subject to all boundary conditions and unit quaternion constraints (2.9) with respect to the kinematic variables $\boldsymbol{r}_i$ and $\boldsymbol{p}_{i+\frac{1}{2}}$.

2.2 Path planning

RQ1 (*routing design*) deals with automatically routing a deformable 1D object in a collision-free way with respect to geometrical design constraints and **RQ3** (*assembly verification*) deals with verifying that the routed design is feasible with respect to assembly. Also, a prerequisite for answering **RQ4** (*production planning*) is having an initial collision-free path. These problems can be stated as *path planning problems*.

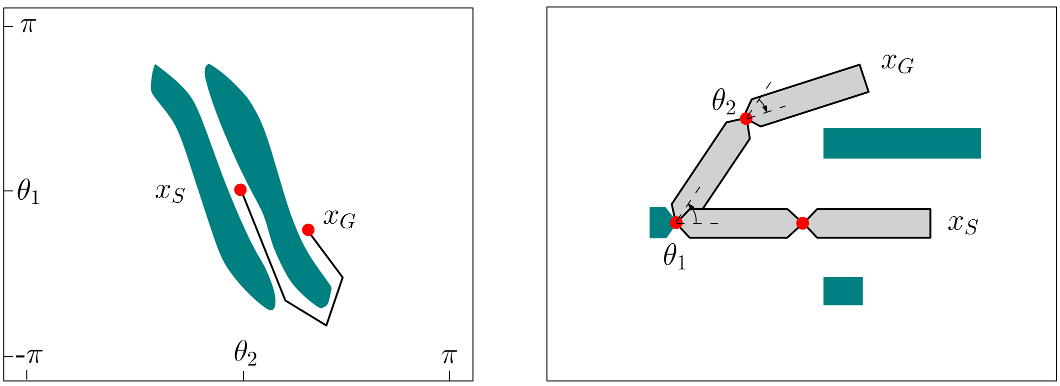
2.2.1 The path planning problem

Consider a geometric object and let $\mathcal{C}$ denote its *configuration space*, i.e. the set of possible configurations of the object. Furthermore, let $\mathcal{C}_{\text{free}} \subseteq \mathcal{C}$ be the subset of configurations for which the geometric object does not collide with any surrounding geometry in its *work space*. A path is then collision-free if all configurations along the path lie in $\mathcal{C}_{\text{free}}$. Typically, a path is represented with a sequence of configurations and an interpolation scheme for determining intermediate path configurations.

> The basic path planning problem is to find a collision-free path in $\mathcal{C}_{\text{free}}$ that continuously takes the object from a starting configuration $x_S \in \mathcal{C}_{\text{free}}$ to a goal configuration $x_G \in \mathcal{C}_{\text{free}}$ or determine that no such path exists (see Figure 2.3).

The path planning problem arises in a wide range of industrial applications, e.g. off-line programming of industrial robots and verifying whether rigid parts can be joined in an assembly. Sometimes, it is desired to additionally optimize some quantity along the path (e.g. robot cycle time) and in other cases, it is the existence of a collision-free path that is of primary interest.

The computational complexity of automatically solving the path planning problem is in general believed to be very high. Determining the existence of a collision-free path has been proven to be NP-complete for the path planning problem in general and PSPACE-hard for polyhedral objects and obstacles in particular (Canny 1988). For a comprehensive introduction to the theory of path planning, the reader is



(a) Configuration space. (b) Work space.

Figure 2.3: A collision-free path between starting and goal configurations for an object with two degrees of freedom.

referred to Latombe (1991), Gupta et al. (1998), Laumond et al. (1998), Choset et al. (2005), and LaValle (2006).

2.2.2 Path planning in practice

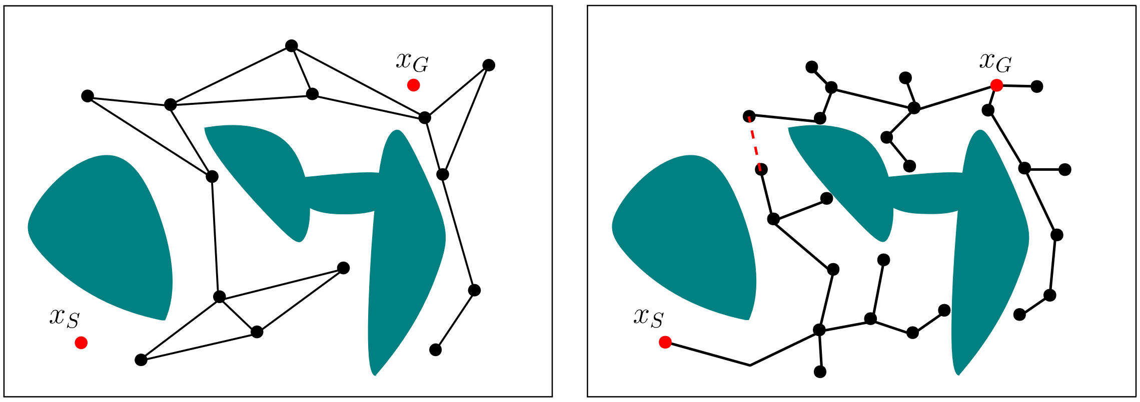
A path planning algorithm is *complete* if it will always find a solution or determine that none exists. Most complete algorithms that exist are geometry-based, for example by using the visibility graph for navigation or cell decomposition (Latombe 1991). However, complete algorithms are of little industrial relevance because they are generally too slow for high-dimensional configuration spaces or when the object and/or the surrounding geometry are represented by potentially millions of polygons.

Potential-based algorithms

Potential-based algorithms are incomplete but can be very efficient in practice. The object is modeled as a moving particle influenced by an artificial potential field on $\mathcal{C}$. The field attracts the particle towards the goal configuration x_G while repelling the particle from the surrounding geometry towards the medial axis of $\mathcal{C}_{\text{free}}$. A drawback of potential-based algorithms is that the particle can get stuck in a local minimum of the potential field and no solution may be found.

Sampling-based algorithms

Sampling-based algorithms trading completeness for speed and simplicity have gained much interest over the years. *Probabilistic complete* algorithms, such as the Probabilistic Roadmap Method (L. Kavraki et al. 1996; Bohlin and L. Kavraki 2000) and Rapidly-Exploring Random Trees (Lavalle 1998), are non-deterministic and capable of finding solutions to problems with many degrees of freedoms (see Figure 2.4). *Resolution complete* algorithms are deterministic and often grid-based and are guaranteed to find solutions to problems with a moderate number of degrees of freedom in finite time with a sufficiently fine resolution (Barraquand et al. 1993;



(a) Probabilistic Roadmap Method (PRM). (b) Rapidly-Exploring Random Trees (RRT).

Figure 2.4: Two sampling-based path planning algorithms.

Bohlin 2001). However, sampling-based algorithms cannot determine if a solution does not exist and are usually terminated after a certain time limit or number of samples have been reached. Common for many sampling-based algorithms are the following components:

Roadmap representation A roadmap of the free configuration space $\mathcal{C}_{\text{free}}$ is maintained as a bi-directed graph consisting of nodes and edges. The roadmap is iteratively updated based on new sampling information.

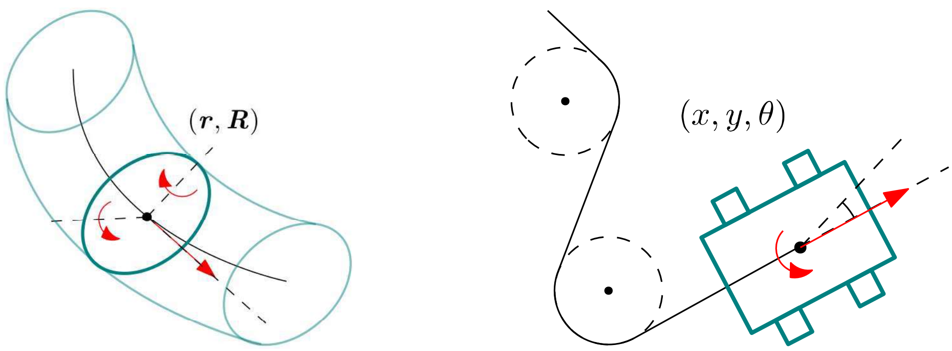
Configuration sampling New configurations in $\mathcal{C}$ are generated according to a certain sampling strategy. The goals of the sampling strategy are mainly generating configurations in areas that have not yet been explored and improving the connectivity of the roadmap.

Nearest neighbor search Whenever a sampled configuration lies in $\mathcal{C}_{\text{free}}$, it is added as a node to the graph. The node is connected with edges to already existing graph nodes in its vicinity, if the interpolated path segment between the corresponding configurations is collision-free. Collision detection, i.e. verifying whether a configuration or path segment is collision-free, is usually the computational bottleneck in a path planning algorithm.

Graph search When enough nodes have been added to the graph, the graph is searched for a path between x_S and x_G using a shortest path algorithm, for example the A* algorithm (pronounced 'A star'). If a path is found, it is a solution to the path planning problem. Otherwise, new sampling information needs to be introduced into the graph and the algorithm continues.

2.2.3 Non-holonomic path planning

From a path planning perspective, routing a 1D object with a constant cross-sectional profile in $\mathbb{R}^3$ can be seen as the problem of finding a collision-free path for a rigid



(a) Routing of a 1D object: 3 controllable degrees of freedom in a 6D configuration space.

(b) Dubin's car: 2 controllable degrees of freedom in a 3D configuration space.

Figure 2.5: Non-holonomic path planning.

2D slice of the cross-section that stays normal to the tangential direction of the path (Figure 2.5a). The path then determines the centerline of the object and the orientation of its cross-sectional plane. This is an example of a *non-holonomic* path planning problem, in which differential constraints reduce the number of controllable degrees of freedom to fewer than the dimension of the configuration space. Analytical solutions have been derived to find the shortest path for car-like vehicles in 2D with curvature constraints (Figure 2.5b) by Dubin (1957) and Reeds et al. (1990). The Probabilistic Roadmap Method has been adapted to different under-actuated robots in the presence of obstacles (Lamiraux et al. 2001; LaValle 2000; Karaman et al. 2013) and deterministic space-filling trees suitable to non-holonomic path planning have been implemented by Kuffner et al. (2011). Specifically, algorithms for routing steerable needles with curvature constraints have been presented by Webster (2006) and Patil et al. (2010).

2.2.4 Path planning for deformable objects

Path planning for deformable objects is widely acknowledged as a challenging problem (L.E. Kavraki et al. 1998). The object's ability to deform geometrically during manipulation adds complexity to the problem. Computing the deformation with a simulation model and performing collision detection become huge computational bottlenecks. Also, the dimension of the configuration space is increased when the object is manipulated with multiple boundary conditions. Another aggravating factor when dealing with non-rigid objects, is that several distinct deformations in static equilibrium (or bifurcation modes) are sometimes possible with the same set of boundary conditions, e.g. contact interaction forcing the object on either side of a part of the surrounding geometry (see Figure 2.6). Nevertheless, there has been limited success in developing path planning algorithms for deformable 1D objects for special cases, most notably by Bretl et al. (2013) and Moll et al. (2006). A survey on manipulation planning for deformable objects is provided by Jiménez (2012).

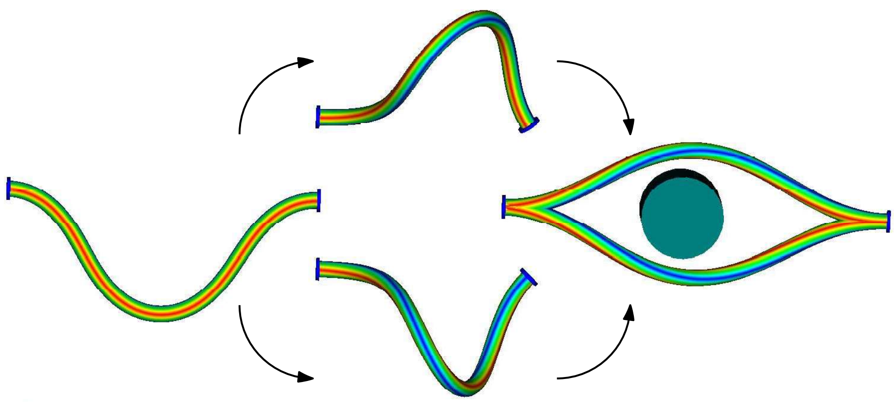


Figure 2.6: Path planning for a deformable 1D object. Two manipulations resulting in two distinct deformations of the object at the goal configuration with the same set of boundary conditions.

2.3 Geometry assurance

Research question **RQ2** (*variation analysis*) deals with evaluating the routed design of a deformable 1D object with respect to geometrical variation.

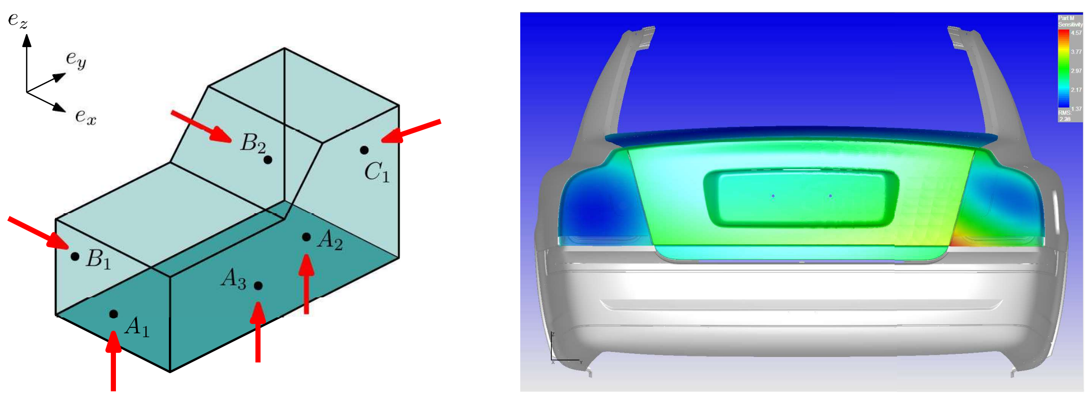
2.3.1 The geometry assurance process

All product realization processes are afflicted by variation. Geometrical variation from manufacturing and assembly propagates and accumulates in production, causing deviation from the reference design in the final product. The *geometry assurance process* is aimed at controlling geometrical variation in a number of activities. In the concept phase, the design is analyzed and optimized with respect to robustness and verified with respect to estimated dimensional tolerances using variation simulation methods (Gao et al. 1995; Cai et al. 1997; Glancy et al. 1999; Söderberg and Lindkvist 1999). In the verification phase, physical prototypes and test-series are used for verification. Non-nominal path planning techniques are used to reduce the need for physical test series (Berg et al. 2011; Carlson, Spensieri, et al. 2013). In the production phase, inspection data is used for diagnosis and root cause analysis (Johnson et al. 1998; Hu et al. 1992; Ceglarek et al. 1996; Jin et al. 2001; Ding et al. 2000a; Ding et al. 2000b; Carlson and Söderberg 2003).

2.3.2 Virtual variation analysis

Virtual tools for robust design and variation simulation of rigid assemblies are well established in industry. The framework proposed by Söderberg, Lindkvist, Wärmefjord, et al. (2016) presents a set of integrated tools for the virtual geometry assurance process. A subset of the tools for virtual variation analysis are:

Stability analysis In stability analysis (Söderberg and Lindkvist 1999), the robustness of the design and the locating scheme (Figure 2.7a) is evaluated. A stability



(a) A 3-2-1 locating scheme.

(b) Color-coding of sensitivity in a rigid assembly.

Figure 2.7

matrix is generated by perturbing the locator positions and computing the resulting displacements of important reference points. This matrix contains first-order information about how the locator positions contribute to design sensitivity. The sensitivity in the reference points is visualized with the help of color-coding (Figure 2.7b).

Variation simulation In variation simulation, the variation in critical measures is evaluated for given statistical distributions and tolerances for the design dimensions. Here, the Monte Carlo simulation method is used. The method generates a large number of random values for the design dimensions according to their distributions and evaluates the critical measures to estimate their statistical properties. The method captures non-linearity and allows for any kind of statistical distribution as input variation.

Tolerance envelope analysis As part of an extensive visualization tool set, tolerance envelope analysis visualizes the effect of geometrical variation by generating a *tolerance envelope* – the smallest possible design space volume enclosing an object when subject to a given set of design tolerances. For a rigid assembly, a tolerance envelope can be generated using convex partitioning and convex hull computations for a large set of variation simulation outcomes (Lööf et al. 2006).

2.3.3 Virtual variation analysis of non-rigid assemblies

For *non-rigid assemblies* (i.e. assemblies consisting of deformable objects), over-constrained locating schemes may be used. There are many significant results related to variation simulation of *deformable 2D objects* such as sheet metal assemblies (Liu et al. 1996; Cai et al. 1997; Ceglarek et al. 1997; Camelio et al. 2004; Lindau et al. 2015). Furthermore, the framework for virtual variation analysis in Section 2.3.2 has been generalized to non-rigid assemblies by Söderberg, Lindkvist, and Dahlström (2006), however not to systems of deformable 1D objects, such as wiring harnesses with multiple branches and break-outs.

Chapter 3

Summary of appended papers

This chapter provides a short summary of the methods developed and the corresponding results from the papers appended to this thesis.

Each appended paper presents a method aimed at answering one of the research questions posed in Section 1.2.1. For each paper, a brief synopsis of the method and a summary of the major results are given. As an illustrative example, the design and verification methods presented in Papers A-D are applied to the industrial use case from the automotive industry shown in Figure 3.1.

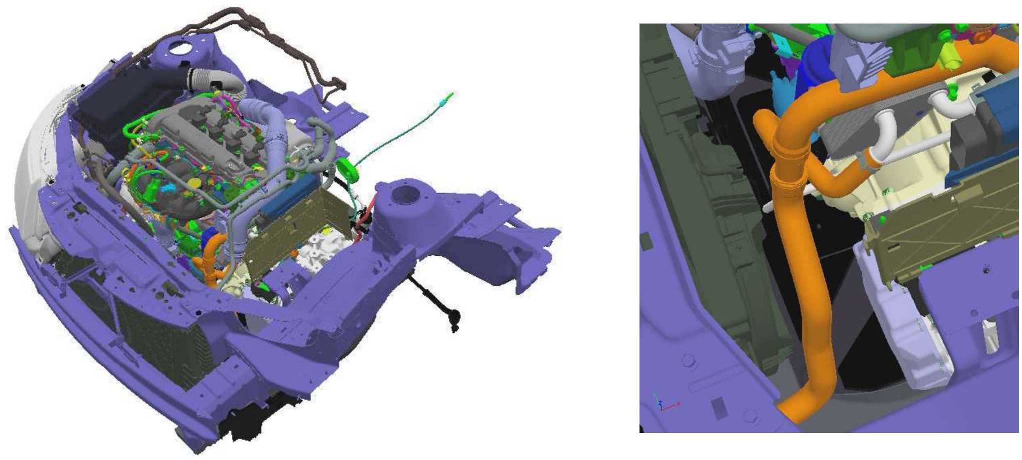
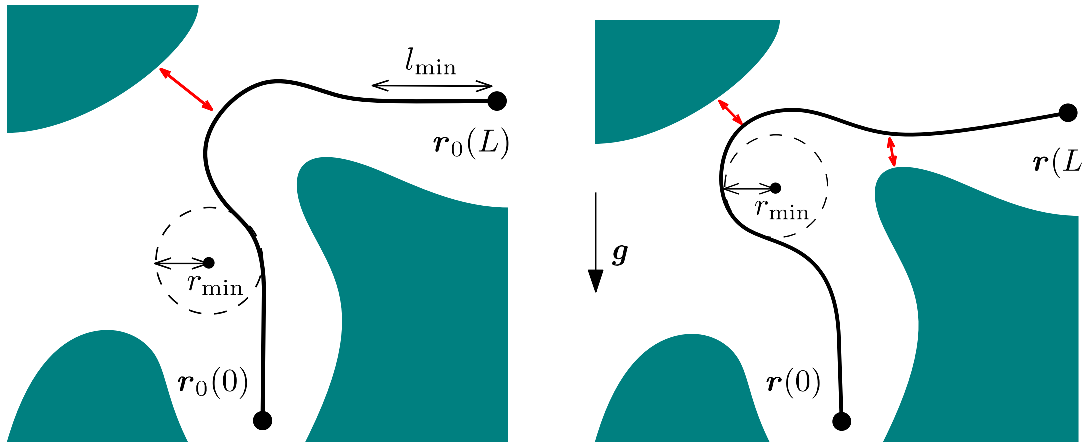


Figure 3.1: An illustrative use case. Three cooler hoses joined in a T-section connecting the radiator with the oil cooler and the engine cooling system in the engine compartment of a car. The geometries are courtesy of NEVS .

3.1 Summary of Paper A

Automatic routing of flexible 1D components with functional and manufacturing constraints

Paper A addresses research question **RQ1** (*routing design*) and proposes a routing method for objects that may become significantly deformed due to gravity in their routed configurations. The method computes a reference design of minimum length and a routed configuration of the object in static equilibrium satisfying a set of geometrical design constraints.



(a) The routed reference centerline of a rod of length L.

(b) The deformed centerline of the rod in static equilibrium.

Figure 3.2: Routing a deformable 1D object subject to geometrical design constraints.

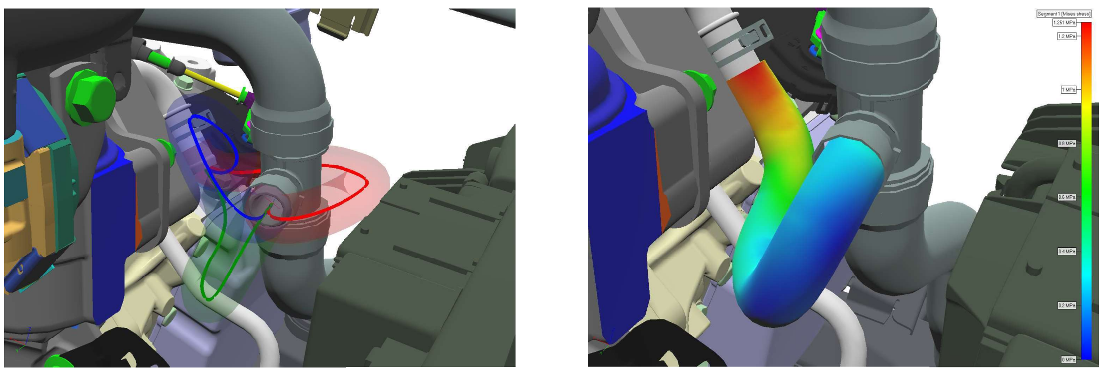
Method synopsis

Let the configuration of a deformable 1D object be determined by a rod configuration (2.5). The goal of the method is to first find a reference rod configuration of minimum length between two connection points that satisfies a set of manufacturing constraints. When subjected to gravity, the rod is most probably deformed from its reference configuration. It is then desired that the rod stays away from surrounding geometry and satisfies a set of functional constraints in static equilibrium.

The problem of routing a reference rod configuration can be stated as a non-holonomic path planning problem (see Section 2.2.3). However, accounting for the deformation of the object is in general far too complex during the course of a path planning algorithm. To remedy this, a segregated method divided into two steps is proposed: In the first step (*nominal routing*), a reference rod configuration is routed between the connection points satisfying a set of manufacturing constraints (e.g. a minimum allowed bending radius or straight segment length). The configuration is optimal with respect to a weighted objective function that gives preference to either short reference length or clearance with the surrounding geometry. In the second step (*local refinement*), using the simulation model in Section 2.1.4 to compute the static equilibrium of the object, the reference length and possibly other adjustable design parameters are optimized with respect to the weighted objective function and a set of functional constraints (e.g. again a minimum allowed bending radius). If a solution is not found, the method may be restarted with a revised objective function.

Nominal routing A collision-free reference rod configuration is computed with a sampling-based path planning algorithm. Assuming that only torsion-free configurations are of interest, the configuration space is $\mathcal{C} = \mathbb{R}^3 \times \mathrm{S}^2$ (i.e. positions and unit tangential directions), whereas there are only three controllable degrees of freedom (moving in the tangential direction and turning around an axis in the cross-sectional plane). A roadmap of $\mathcal{C}_{\text{free}}$ is constructed from all collision-free nodes on a uniform rectangular grid and the nodes are connected with edges if their corresponding positions and tangential directions can be joined without violating the manufacturing constraints. A shortest path (with respect to the weighted objective function) is computed between the connection points using the A^* algorithm. If a solution path is found, it determines the reference rod configuration.

Local refinement If a reference rod configuration was found in the *nominal routing* step, it is used to initialize a discrete Cosserat rod model (Section 2.1.4). A corresponding rod configuration in static equilibrium is computed from (local) minimization of the total potential energy, i.e solving (2.4). The weighted objective function, with an added penalty term to enforce that the functional constraints are satisfied, is (locally) optimized with respect to the adjustable design parameters (e.g. the reference length and/or orientation of the connection points). As each evaluation of the weighted objective function requires that static equilibrium is computed, a gradient-free algorithm for unconstrained non-linear programming is used. If an acceptable solution is not found, either the *nominal routing* step is



(a) Reference design alternatives corresponding to different objective function weights after *nominal routing*.

(b) The hose with the green reference design in static equilibrium after *local refinement*.

Figure 3.3: Routing design of the cooler hose from the T-section to the oil cooler in the illustrative use use case (Figure 3.1).

restarted with a revised set of objective function weights or clips are introduced along the reference rod configuration to control the deformation.

Results

A method for routing a deformable 1D object subject to large deformations was presented in Paper A and was implemented in the IPS software. To account for deformation, the method was divided into a global path planning step and a local simulation-based optimization step.

- The method was verified and analyzed on an academic benchmark case and was successfully applied to an industrial use case of routing an AC cooler hose in a densely packed engine compartment. The geometry was described with more than 1 million triangles and running times were less than a minute.
- The method can be used for objects that are not preformed, i.e. objects with a straight reference configuration. A rod configuration satisfying the functional constraints is then generated in the *nominal routing* step and used as the initial rod configuration for the *local refinement* step.
- The *local refinement* step can be used as a stand-alone procedure to optimize the reference design of a deformable 1D object if an initial configuration is already given.
- The *local refinement* step is in this paper implemented using a gradient-free algorithm for unconstrained non-linear programming in which the simulation model is evaluated as a black-box. Paper E proposes a (quasi-static) parameter optimization framework that includes the static equilibrium equations as constraints in a constrained non-linear optimization problem formulation. Using this framework might help further improve the computational performance, since more information about the structure of the problem is exposed to a non-linear programming algorithm than when using a black-box solution.

3.2 Summary of Paper B

Automatic routing of preformed hoses

Paper B addresses research question **RQ1** (*routing design*) and proposes a routing method for preformed hoses that are not significantly deformed due to gravity in their routed configurations. The method generates a set of reference design alternatives for an experienced design engineer to choose from.

Method synopsis

Let the reference configuration of a preformed hose be determined by a rod configuration (2.5) in a specific form: Assuming that preformation is the process of gradually applying a sequence of bends, each with a constant bending radius and a straight segment of sufficient length in between, the rod centerline is a sequence of circular arcs joined by straight line segments (Figure 3.4). This family of curves are denoted *piecewise-constant-curvature* (PCC) curves. Rather than finding a single optimal reference design, the goal of the method is to generate a *set* of collision-free PCC curves that are locally of minimum length and satisfy a set of geometrical design constraints in the form of a minimum allowed bending radius and a minimum allowed straight segment length. It is desired that the curves in the set are topologically different (i.e. they are routed through different regions of $\mathcal{C}_{\text{free}}$ or have a different number of arcs).

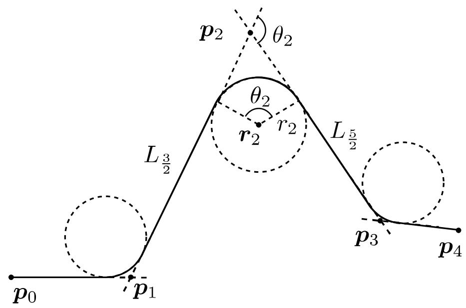
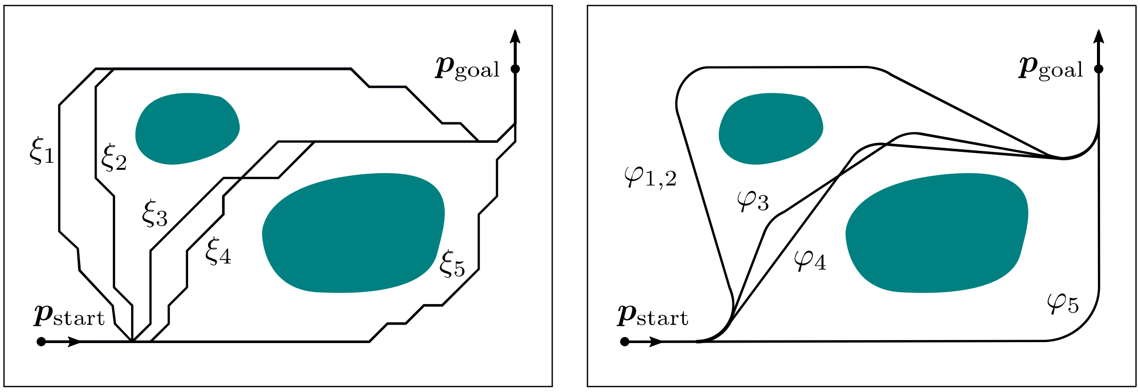


Figure 3.4: The PCC curve representation.

The problem of routing a collision-free PCC curve can be stated as a non-holonomic path planning problem (see Section 2.2.3). In fact, in $\mathbb{R}^2$ and in the absence of surrounding geometry, a PCC curve of minimum length is a Dubin's curve which has an analytical closed form solution (Dubin 1957). However, in $\mathbb{R}^3$ and in the presence of surrounding geometry, the situation is far more complex. To remedy this, a sampling-based algorithm in four steps is proposed: In a *global search*, a large set of piecewise linear paths is generated. From this set, a set of PCC curve candidates is sampled with as few arcs as possible (*PCC curve sampling*). Then, each PCC curve candidate is locally optimized with respect to arc length and the design constraints (*PCC curve optimization*). In a final filtering step, all PCC curves



(a) The set of piecewise linear paths after the *global search* step.

(b) The set of feasible PCC curves after the *PCC curve filtering* step.

Figure 3.5

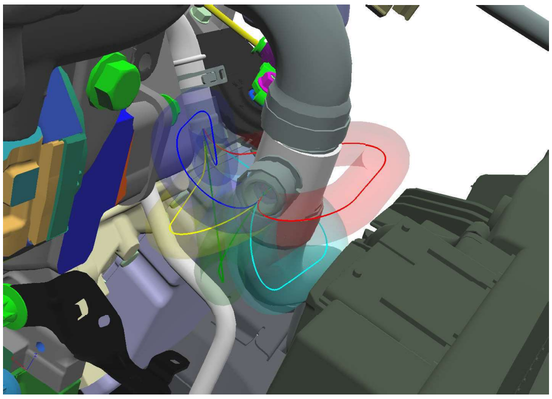
that are either infeasible or considered identical to other PCC curves are removed from the set (*PCC curve filtering*).

Global search A roadmap is constructed over $\mathbb{R}^3$ consisting of all nodes on a uniform rectangular grid that are collision-free. Each node is connected with edges to the other nodes in the roadmap that can be reached with collision-free line segments in all canonical and diagonal grid directions. Given a starting node and a goal node, the graph is repeatedly searched for the shortest path, which is added to a set of consequently piecewise linear paths. For each added path, all nodes within a certain distance are excluded from the roadmap. The search is ended when a shortest path can no longer be found.

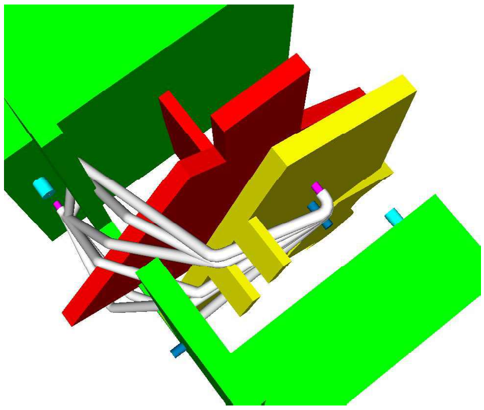
PCC curve sampling From the set of piecewise linear paths, a set of initial PCC curve candidates is sampled with as few arcs as possible and with similar segment lengths. For each original path, the shortest path with a fixed number of equidistant vertices is computed by taking shortcuts between the original vertices. The process is repeated until the maximum allowed number of arcs has been reached. For each new path, the PCC curve defined by its vertices (and a bending radius of zero) is added to a set of PCC curve candidates.

PCC curve optimization The initial PCC curve candidates are most likely infeasible with respect to the design constraints. Hence, an unconstrained non-linear minimization problem is formulated with an objective function that rewards curves with short arc length and penalizes infeasibility and collision with surrounding geometry. For each initial PCC curve candidate, the minimization problem is solved using the curve as the initial solution. If an optimal and feasible solution exists, it is added to a set of feasible PCC curve candidates.

PCC curve filtering The set of feasible PCC curve candidates is likely to contain identical curves, as many initial PCC curves might have converged to the same



(a) Reference design alternatives for the cooler hose from the T-section to the oil cooler for the illustrative use case (Figure 3.1).



(b) Reference design alternatives for a preformed hose in a test case from Volvo Cars.

Figure 3.6: Routing design of preformed hoses.

locally optimal solution. The set is therefore pruned from identical curves by first identifying all identical curves using a curve distance metric and then keeping the best ones in terms of arc cardinality and optimal objective function value from the *PCC curve optimization* step.

Results

A method for routing a preformed hose on the form of a piecewise-constant-curvature curve was presented in Paper B and was implemented in the IPS software. The method uses a global search to generate a set of PCC curve candidates that are then optimized subject to geometrical design constraints, resulting in a set of reference design alternatives that are topologically different and locally of minimum length.

- The method was verified and analyzed on an academic benchmark case and was successfully applied to an industrial test case (Figure 3.6b) and an industrial use case of routing a transmission oil cooler hose next to an already routed hose.

- The implementation of the method relies on parallelization and running times were in the magnitude of seconds. The *PCC curve optimization* step was identified as the most time-consuming step.

- The method generates a set of reference design alternatives, so that when presented to an experienced engineer, the engineer can pick the best design alternative with respect to subjective properties that cannot necessarily be quantified by an objective function.

- As deformation is not considered, the method is a complement to the routing method presented in Paper A for preformed objects that are not significantly deformed.

3.3 Summary of Paper C

Geometric variation simulation and robust design for flexible cables and hoses

Paper C addresses research question **RQ2** (*variation analysis*) and proposes a methodology for analyzing and visualizing the effect of geometrical variation for a deformable 1D object in a given configuration. In particular, a method is developed for generating a tolerance envelope, i.e. the design space volume possibly occupied by an object when subject to geometrical variation.

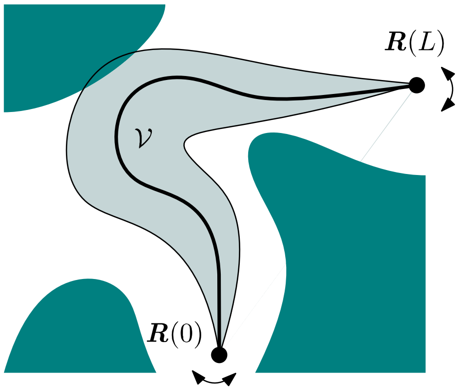


Figure 3.7: A tolerance envelope of a deformable 1D object subject to rotational variation in the connection points.

Methodology synopsis

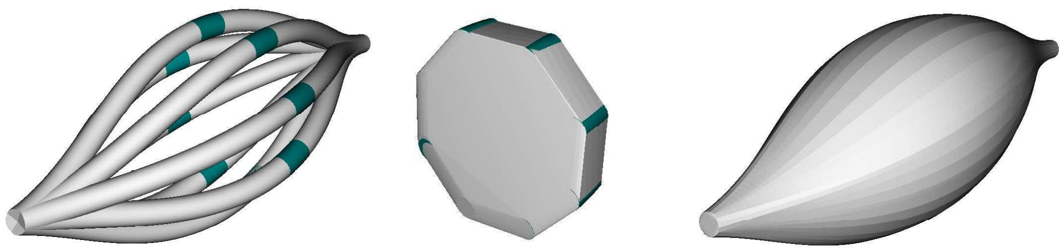
Consider a system of deformable 1D objects held in place at a set of connection points. Let the system be affected by geometrical variation in a set of design dimensions, e.g. the reference length of an object in the system or the positions and orientations of a connection point. Hence, the configuration of the system in static equilibrium depends implicitly on a set of stochastic design variables collected in a vector $\boldsymbol{X} = (X_1, \ldots, X_n)^T$, each x_i belonging to a statistical distribution and having a symmetrical tolerance $[t_i^-, t_i^+]$ about its nominal value $\bar{X}_i$. A set of critical measures $\boldsymbol{Y} = (Y_1, \ldots, Y_m)^T$ may also be defined for the system in static equilibrium as functions of the stochastic design variables, i.e. $\boldsymbol{Y} = \boldsymbol{Y}(\boldsymbol{X})$. Variation analysis is now the task of evaluating the robustness of the given system configuration with respect to the design variables and performing a variation simulation in order to estimate the statistical distributions of $\boldsymbol{Y}$ and to visualize the effect of geometrical variation.

The methodology extends the virtual variation analysis framework for rigid and non-rigid assemblies described in Section 2.3.2 and consists of *stability analysis*, *variation simulation* and *tolerance envelope analysis*. The generalization to a system of deformable 1D objects is conceptually straightforward using the discrete Cosserat rod model (Section 2.1.4) to enable accurate and computationally efficient computations of the deformation. Each outcome of the design variables yields a different configuration of the system for which the critical measures can be evaluated. Hence, the static equilibrium needs to be computed for each outcome. For the first-order *stability analysis*, this evaluation is almost insignificant in terms of computational performance. However, in a full-scale *variation simulation* with the Monte Carlo method, the necessary number of random evaluations may become huge. Also, it shall be noted that even for small tolerances, it is important that deformations are indeed accurately computed in order to identify non-robust designs.

Tolerance envelope analysis

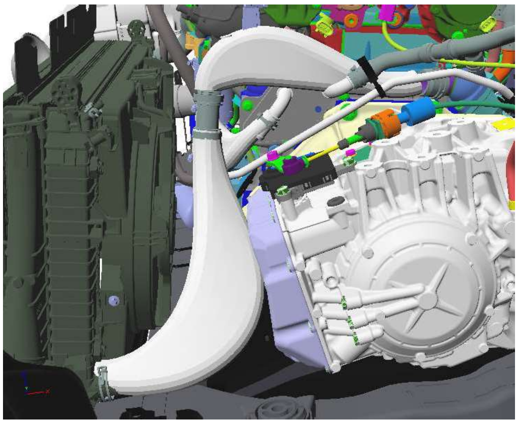
The main innovation presented in the paper is a method for generating a tolerance envelope for a system of deformable 1D objects. Formally, let $S(\boldsymbol{x}) \subset \mathbb{R}^3$ be the volumetric shape of the system in static equilibrium that corresponds to the design variable values $\boldsymbol{x}$. A tolerance envelope is then defined as the smallest possible volume $\mathcal{V} \subset \mathbb{R}^3$ enclosing the objects when subject to a given set of design tolerances, i.e. $\mathcal{S}(\boldsymbol{x}) \subseteq \mathcal{V}$ must hold for all $\boldsymbol{x}$ such that $x_i \in [\bar{X}_i - t_i^-, \bar{X}_i + t_i^+]$. By construction, the tolerance envelope is a worst case visualization of the design space possibly occupied by the object.

To generate a discrete approximation of a tolerance envelope, variation simulation is first used to sample a spanning set of outcome configurations of the system in static equilibrium. As a tolerance envelope is a worst case visualization, the aim is to generate a spanning set of outcomes as evenly distributed as possible. Therefore, the Monte Carlo method is used to generate design variables values from a uniform statistical distribution defined on the tolerance domain. The volumetric shape of a deformable 1D object is approximated as a chain of triangulated cylinders representing its boundary surface. A discrete approximation of the boundary $\partial\mathcal{V}$ is then obtained by generating the convex hull of each cylinder as it assumes all its configurations in the spanning set, and then taking the union of all convex hulls (see Figure 3.8). Besides the obvious computational bottleneck in computing the static equilibrium, there is a potential build-up in required memory to store the discrete tolerance envelope. To overcome this, all interior patches are removed from

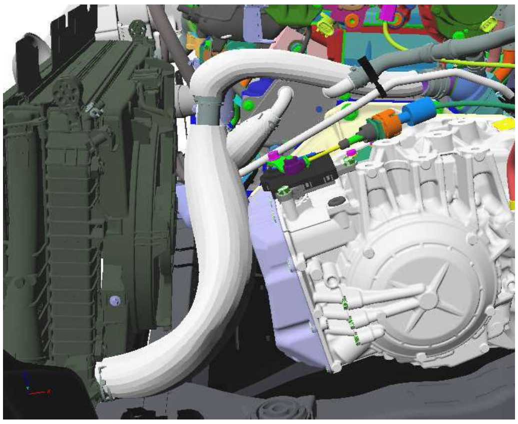


(a) Spanning set of configurations. (b) Convex hull of a cylinder's configurations. (c) Union of all convex hulls.

Figure 3.8: Generation of a tolerance envelope.



(a) Tolerance envelope with respect to a length tolerance of ±50 mm for each hose.



(b) Tolerance envelope with respect to a rotational cone tolerance of ±15° for each hose connection.

Figure 3.9: Tolerance envelope analysis for the illustrative use case (Figure 3.1).

the envelope after the union operation in a post-processing step by employing a marching cube algorithm and keeping only the boundary surface.

Results

A methodology for analysis and visualization of the effect of geometrical variation for a system of deformable 1D objects was presented in Paper C and the tolerance envelope analysis was implemented in the IPS software. The methodology expands the virtual variation analysis framework proposed by Söderberg and Lindkvist (1999).

- The methodology was successfully applied to two industrial use cases.
- The discrete Cosserat rod model enabled a computationally efficient variation simulation based on the Monte Carlo method.
- The main innovation is the method for generating a tolerance envelope for a system of deformable 1D objects. The method is based on convex hull computations and boundary surface extraction.
- The generation of the tolerance envelopes for the illustrative use case (Figure 3.9) takes 2-3 seconds when performing 1000 Monte Carlo iterations.

3.4 Summary of Paper D

Automatic assembly path planning for wiring harness installations

Paper D addresses research question **RQ3** (*assembly verification*) and proposes a method for verifying whether there exists an assembly manipulation that takes a system of deformable 1D objects to its routed configuration. When the verification is true, the method outputs a feasible assembly manipulation that can be useful in production planning.

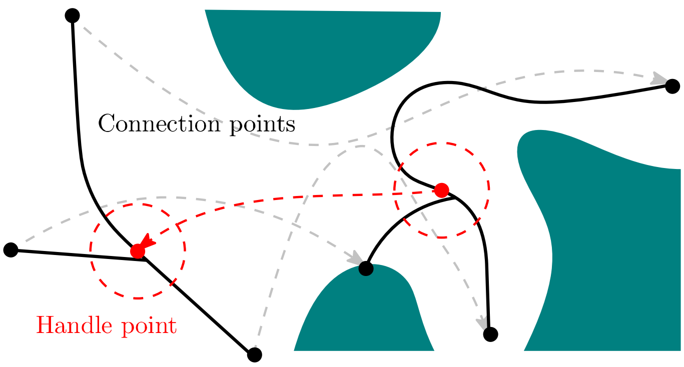


Figure 3.10: Assembly manipulation taking a system of deformable 1D objects to its routed configuration. The trajectory of the handle point after the *handle path planning* step is illustrated in red.

Method synopsis

Consider a system of deformable 1D objects held in place with a set of connection points and let the configuration of each object be determined by a rod configuration. Let a manipulation of the system be a synchronized set of paths for the connection points. The goal of the method is to find an assembly manipulation that moves the system from an initial configuration to its routed configuration in a quasi-static motion without stretching or bending the object more than necessary and while staying away from surrounding geometry.

There are several challenges associated with path planning for deformable objects (see Section 2.2.4). When there are multiple connection points, the problem becomes high-dimensional. Also, several distinct configurations in static equilibrium are sometimes possible for the same set of boundary conditions, which might have the effect that an assembly manipulation does not take the system to the routed configuration even though the connection points are aligned. To remedy this, a method divided into four steps is proposed: First, the system is placed in its routed configuration and all connection points are released (*grip point relaxation*). The system is then pulled away from the surrounding geometry in a temporarily introduced handle point and unfolded (*handle path planning*). During this process, the path of each free connection point is traced and stored. The paths are then reversed, smoothed and joined in a synchronized assembly manipulation (*path smoothing*). In a final step, contact interactions with the surrounding geometry during the assembly manipulation (if any) are resolved by adding supplementary connection points (*grip point supplementation*).

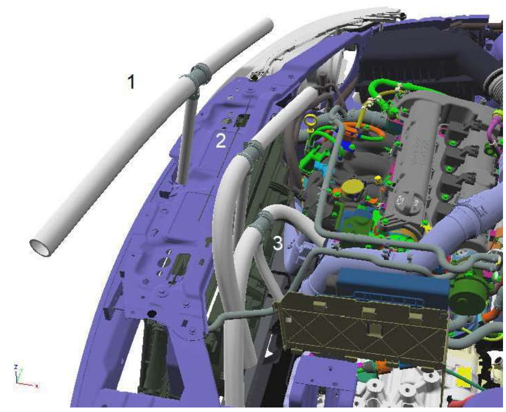
Constraint relaxation First, an additional handle point is added as a boundary condition at a central location on the system in its routed target configuration. Then, all connection points are set free by removing the corresponding boundary conditions in the system. The system will assume a configuration in static equilibrium held in place by an external force and moment at the handle point and by external contact forces from surrounding geometry. When computing the static equilibrium by minimizing the total potential energy of the system, the path of each (free) connection point during the minimization process is traced and stored.

Handle path planning A collision-free path is now generated for a ball $B_r \in \mathbb{R}^3$ with a radius $r > 0$ starting from the routed position of the handle point to a target position far away from surrounding geometry. This is a low-dimensional path planning problem in $\mathbb{R}^3$ and is solved with a sampling-based algorithm on a uniform rectangular grid. If a collision-free path is found with respect to surrounding geometry for a sufficiently large[1] ball radius r, the handle point is moved along the path and the configuration of the system in static equilibrium is computed. The system will passively follow the handle point due to being pulled by internal forces and moments and will ultimately unfold when far away from the (no longer) surrounding geometry. Again, the path of each connection point during the motion is traced and stored.

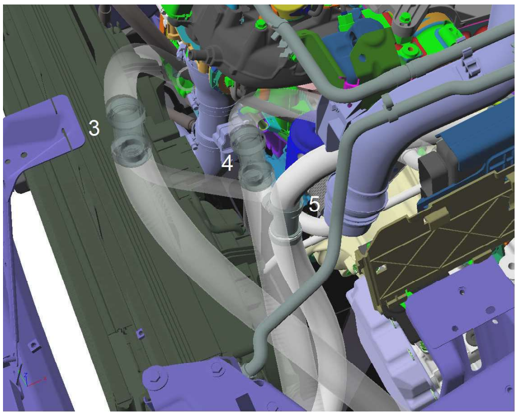
Path smoothing For each connection point, the stored path is reversed so that it ends in the routed position of the connection point. Next, the path is modified in order to reduce peaks in curvature and to allocate more clearance along the path using a heuristic smoothing procedure. Together, the smoothed paths constitute an assembly manipulation for the system.

Grip point supplementation Finally, when applying the assembly manipulation to the system, undesired contact between the system and surrounding geometry might still occur. This can be resolved by attaching one or several supplementary handle points to the system. If a feasible assembly manipulation is still not found, the verification is false and it might be necessary to change the reference design of the system.

[1] The ball radius r should at least be larger than the radii of all the deformable 1D objects in the system.



(a) The first part of the assembly manipulation.



(b) The final part of the assembly manipulation.

Figure 3.11: Assembly manipulation for the illustrative use scenario (Figure 3.1).

Results

A method for verifying whether there exists an assembly manipulation that takes a system of deformable 1D objects from an initial configuration to its routed configuration was presented in Paper D and implemented in the IPS software. To deal with the challenges in high-dimensional path planning for deformable objects, a method that tries to pull the system from its routed configuration in one low-dimensional global path planning step followed by three local simulation-based post-processing steps was proposed.

- The method was verified and analyzed on an academic benchmark case and was successfully applied to an industrial use case of assembly verification of a wiring harness.
- If the verification is true, the method outputs an assembly manipulation that can be useful in production planning.
- The *constraint relaxation* step can be used as a stand-alone procedure to transform a system of deformable 1D objects from a routed configuration to its reference configuration by first removing the gravity field and all surrounding geometry. This transformation is in industry sometimes referred to as *flattening*.
- The running time for the industrial use case was in the magnitude of minutes. The implementation of the method relied on an early version of the simulation model that used a quasi-Newton algorithm for the minimization of total potential energy. Hence, the computational performance did not scale well for a system with its number of deformable 1D objects. With a Newton-based algorithm, however, it can be expected that the performance scales linearly with the size of the system and that the running time is significantly reduced for large systems.

3.5 Summary of Paper E

Quasi-static path optimization for industrial robots with dress packs

Paper E addresses research question **RQ4** (*production planning*) and proposes a method for performing path optimization for an industrial robot with a dress pack. Given a planned path for the robot, the path is modified to account for the deformations of the dress pack.

Method synopsis

Consider a collision-free path for an industrial robot between two starting and goal configurations and that the path has been generated by a robot path planning algorithm without the robot dress pack considered. Let the path be described by a set of via point configurations of the robot and a linear interpolation scheme. Furthermore, assume that the dress pack is deformed quasi-statically when attached to the moving robot. The goal of the method is then – if necessary – to modify the path (i.e. moving the via point configurations) so that the dress pack is not stretched or bent more than necessary and stays away from surrounding geometry during the robot motion.

The problem of optimizing a motion of a dynamic mechanical system with respect to a control signal is the fundamental problem in optimal control theory. As only quasi-static motions of the system are considered, a method based on a quasi-static parameter optimization problem formulation is proposed. Assume that an initial path of duration $T > 0$ with a fixed number of via points is given for the robot and let U be the set of all possible via point configurations. Furthermore, let the mechanical system be defined by the robotic manipulator and the deformable dress pack modeled as a discrete Cosserat rod (Section 2.1.4) with its connection points attached to the robot. Let $Q \in \mathbb{R}^n$ be the set of possible configurations of the system. The quasi-static parameter optimization problem is then to find a set of via point configurations $\boldsymbol{u} \in U$ so that, for the corresponding motion of the system, the following is achieved:

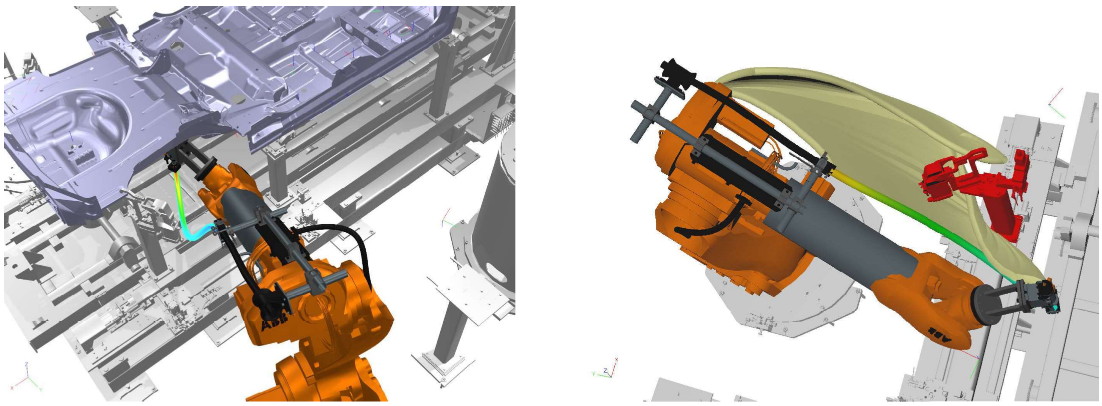
- An objective function $\mathcal{F} : Q \times U \times [0, T] \mapsto \mathbb{R}$ is minimized during the motion of the system. The objective function penalizes tension force in the connection points and rewards short paths with uniform velocity.
- The static equilibrium equations (2.3) are satisfied for the dress pack model at all times.
- A set of d additional inequality constraints defined by a constraint function $\boldsymbol{h} : Q \times [0, T] \mapsto \mathbb{R}^d$ are satisfied at all times. Additional constraints can, for example, be geometrical design constraints and/or clearance requirements for the robot and the dress pack with respect to surrounding geometry.

Numerical solutions

A direct way to obtain numerical solutions is to discretize the problem in time and transcribe it into a non-linear programming problem, for which the constraints must hold at discrete times. For a uniform time discretization $0 = t_1 < t_2 < \ldots < t_N = T$, the problem then reads

$$\begin{aligned}
&\text{Minimize } \sum_{k=1}^{N} \mathcal{F}(\boldsymbol{q}_k, \boldsymbol{u}, t_k) \\
&\text{subject to} \\
\frac{\partial V}{\partial \boldsymbol{q}_i}(\boldsymbol{q}_i) + \boldsymbol{\lambda}_i \cdot \frac{\partial \boldsymbol{g}}{\partial \boldsymbol{q}_i}(\boldsymbol{q}_i, \boldsymbol{u}, t_i) &= \mathbf{0}^n, \quad i = 1, \ldots, N, \\
\boldsymbol{g}(\boldsymbol{q}_i, \boldsymbol{u}, t_i) &= \mathbf{0}^m, \quad i = 1, \ldots, N, \\
\boldsymbol{h}(\boldsymbol{q}_i, t_i) &\geq \mathbf{0}^d, \quad i = 1, \ldots, N.
\end{aligned}$$

The variables in the problem are the via point configuration vector $\boldsymbol{u} \in U$ and the system configuration $\boldsymbol{q}_i \in Q$ and the system constraint multipliers $\boldsymbol{\lambda}_i \in \mathbb{R}^m$ at all times t_i. Hence, the problem becomes large-scale even for moderately large time steps, stressing the importance of having a simulation model described with as few degrees of freedom as possible. The problem is solved for a locally optimal solution using an interior-point algorithm by starting from an initial solution constructed from a simulation of to the initial path for the robot.



(a) Problematic robot configuration regarding the dress pack.

(b) Sweep of the dress pack during the optimized robot path.

Figure 3.12: Path optimization for a robot with respect to the dress pack.

Results

A method for path optimization for an industrial robot with a dress pack was presented in Paper E and implemented in the IPS software. The dress pack was modeled as a discrete Cosserat rod and a quasi-static parameter optimization problem was formulated with an objective function that penalizes tension force in the connection points and rewards shorter paths of uniform velocity.

- The method was successfully applied to an industrial use case of an industrial robot moving in-between stud-welding locations in a stud-welding station. The running times were in the range of 1-3 minutes for more problematic robot paths and within seconds for less problematic paths.

- The method was implemented with assembly path optimization for industrial robots in mind. However, the (quasi-static) parameter optimization framework might be used also for other applications. For example, improving assembly manipulations found by the method for assembly verification presented in Paper D and for the *local refinement* step in the routing method presented in Paper A.

Chapter 4

Discussion

> This chapter discusses the research results in relation to the research questions, validation and verification and its scientific and industrial contribution.

4.1 Answers to the research questions

The research scope of this thesis was defined by the four research questions posed in Section 1.2.1. This section discusses the answers to the research questions and to which extent the success criteria defined in Section 1.2.2 have been fulfilled.

> **RQ1** How can a deformable 1D object be automatically routed in a collision-free way with respect to geometrical design constraints? (*routing design*)
>
> *This research question was answered by developing two methods for routing design.*

A method for routing a deformable 1D object subject to large deformations was presented in Paper A. To account for deformation, a method divided into a global path planning step and a local simulation-based optimization step was proposed. The method was analyzed and verified on an academic benchmark case and an industrial use case. The method has since been implemented in the IPS software and is today used at several companies in the automotive industry, e.g. BMW and Ford.

Another method for routing a preformed hose represented by a piecewise-constant-curvature curve was presented in Paper B. A global search is used to generate a set of PCC curve candidates that are then optimized with respect to design constraints, resulting in a set of reference design alternatives that are topologically different and locally of minimum length. The method was implemented in a demonstrator version of the IPS software in the research project and was incorporated in a machine learning framework developed by Linköping University of Technology. The results were validated by engineers at Volvo Cars.

RQ2 How can the routed design of a deformable 1D object be analyzed with respect to geometrical variation? (*variation analysis*)

This research question was answered by developing a methodology for variation analysis.

A methodology for analysis and visualization of the effect of geometrical variation for a system of deformable 1D objects was presented in Paper C. The methodology extends the virtual analysis framework proposed by Söderberg and Lindkvist (1999) towards systems of deformable 1D objects. The methodology was verified on two industrial use cases. The method for tolerance envelope analysis has since been implemented in the IPS software and is today used at several companies in the automotive industry, (e.g. Volvo Cars and Ford (internally referred to as *tolerance zones*).

RQ3 How can it be verified that the routed design of a deformable 1D object is feasible with respect to assembly? (*assembly verification*)

This research question was answered by developing a method for assembly verification.

A method for verifying that there exists an assembly manipulation that takes a system of deformable 1D objects from an initial configuration to its routed configuration was presented in Paper D. To deal with the challenges in high-dimensional path planning for deformable objects, a method that tries to pull the system from its routed configuration in one low-dimensional global path planning step and three local simulation-based post-processing steps was proposed. If the verification is true, the method outputs an assembly manipulation that can be useful when planning the assembly operation. The method was analyzed and verified on an academic benchmark case and an industrial use case. The method has since been added to the API of the IPS software and is used at several industrial companies (e.g. Ford). An application is *harness flattening*, i.e. transforming a wiring harness from a routed configuration to its reference configuration.

RQ4 How can a planned path be optimized with respect to deformable 1D objects in the product and/or production system? (*production planning*)

This research question was answered by developing a method for path optimization.

A method for path optimization of an industrial robot with a dress pack was presented in Paper E. The dress pack was modeled as a Cosserat rod and a quasi-static parameter optimization problem was formulated with an objective function that penalizes tension force in the connection points and rewards shorter paths of uniform velocity. The method was analyzed and verified on an industrial use case of a stud-welding station at Volvo Cars. The method was implemented in a demonstrator version of the IPS software within the research project for optimization of robot programs.

4.2 Evaluation of success criteria

The ultimate success criterion for evaluating the research results was tied to the fulfillment of answering the research questions by having developed methods consistent with the method requirements (Section 1.2.2). The measurable success criteria were evaluated as follows:

Compatibility All methods were implemented in the IPS software and have therefore inherited compatibility with a variety of standard geometry file formats such as JT and VRML and the possibility to export optimized robot programs. Design solutions for deformable 1D objects were stored in the open XML-based HMD (Harness Model Description) format.

Accuracy In the simulation-aided methods, the deformable 1D objects were modeled as discrete Cosserat rods. This enables accurate computations of large non-linear deformations in agreement with the real-world objects (see Section 1.3.2). The collision detection was performed using a library that computes the exact distance (to machine accuracy) with respect to both point clouds and triangulated geometry using bounding-volume hierarchies.

Speed The performance of the simulation-based methods relies on the underlying simulation model. The discrete Cosserat rod model constitutes a very compact representation of a 1D object that enables an efficient computation of the deformation by means of energy minimization. To deal with the challenges in high-dimensional path planning for deformable objects, the methods were divided into global path planning steps and local simulation-based steps. The running times for all methods on typical industrial use cases were in the range of seconds up to 10 minutes.

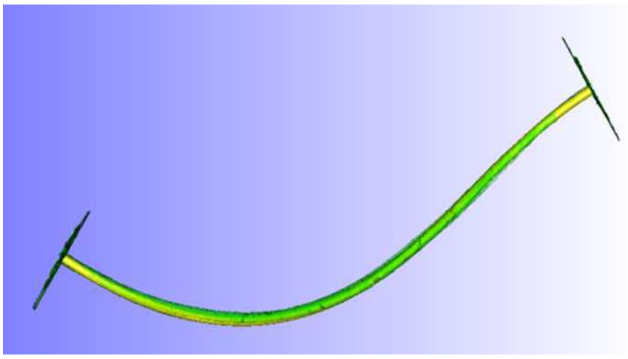
Contribution All methods developed have novel elements and have undergone peer-review by experts in the relevant research areas and have been shared[1] with the scientific community in well-regarded journals.

[1]Paper B was at the time of the writing of this thesis still under review.

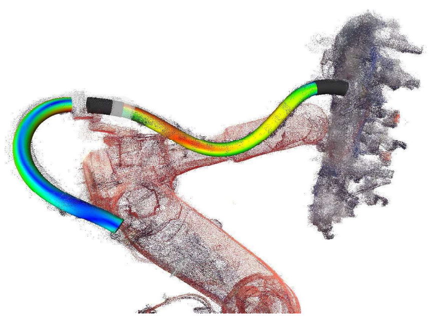
4.3 Validation and verification

The methods were validated by having been tested on industrial use cases by industrial partners in the research projects and by being used in a software with a global user base. It is difficult to assess and obtain data on how much one isolated method has improved the manufacturing performance at a specific company. Volvo Cars states in general that "using the IPS software early in the development process prevents quality problems later on and significantly reduces development time and need of physical testing" and that "the automatic tools allow for reducing non-utilized design space by placing components closer to each other without compromising quality". Also, in a case study on a hydraulic hose in the lifting function of a wheel loader made by the hydraulic hose manufacturer HydroSpecma in the IPS software, "the new routing design reduced the stress by 30 percent, which significantly decreased the risk of downtime and field claims.".

The simulation results were validated by comparison with measurements on real-world objects performed by industrial partners in research projects. For example, in Figure 4.1a, a visual comparison was made between a rod model and a scanned point-cloud of a cable specimen from Delphi (see also Paper C) and in Figure 4.1b, a similar comparison was made for a robot dress pack from ABB. Naturally, the validity of the simulation results also depend on supplying authentic material parameters to the model. Physically correct material parameters may, for example, be identified using a measurement system, e.g. MeSOMICS.



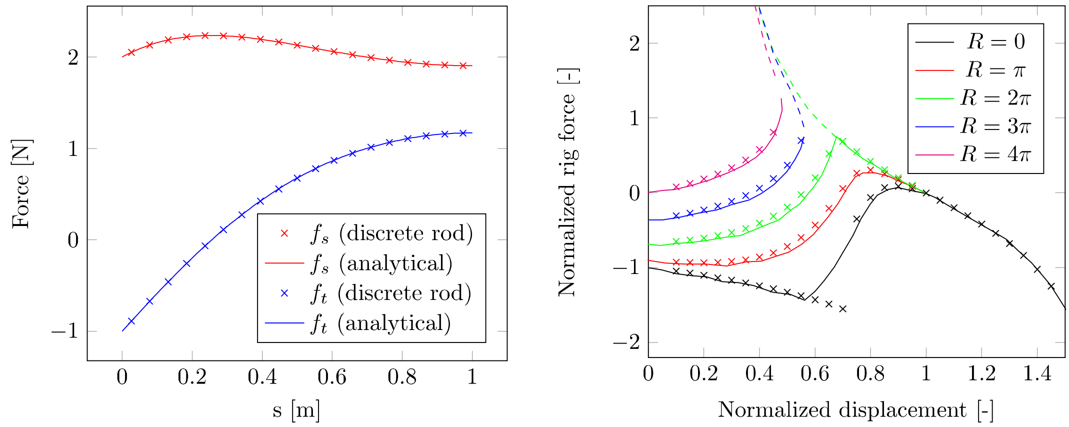
(a) Visual comparison between the discrete rod model and a CT scan of a cable (courtesy of Delphi). The maximum deviation was less than 2 mm.



(b) Visual comparison between the discrete rod model and a CT scan of a robot dress pack (courtesy of Volvo Cars).

Figure 4.1: Validation of the simulation model.

The research results were verified with the *verification by acceptance* approach (see Section 1.3.2). The methods were presented in scientific papers that were accepted after having undergone a peer-review process by experts in the relevant research areas. Thereby, the methods were found to be consistent with existing theory and their scientific contribution was verified. In order to verify the properties of the simulation model, two conference papers (Linn et al. 2017; V. Dörlich et al. 2019) that are not included in but relevant to this thesis were shared with the multibody dynamics community. In the papers, simulation results from the discrete Cosserat rod model were compared with well-known academic cases for which analytical solutions are known (see Figure 4.2).



(a) Internal forces in a discrete Cosserat rod in static equilibrium compared with the analytical solution of an *elastica* of length 1 m.

(b) The discrete Cosserat rod model compared with numerical results from the experiment by G. H. M. van der Heijden et al. (2003) for a different set of pre-applied twists R.

Figure 4.2: Verification of the simulation model.

4.4 Scientific and industrial contribution

The contribution of the research presented in this thesis is summarized as follows:

Scientific contribution

- A novel method for routing a deformable 1D object subject to large deformations and geometrical design constraints (Paper A).
- A novel method for routing a preformed hose on the form of a piecewise-constant-curvature curve (Paper B).
- A novel method for generating a tolerance envelope for a system of deformable 1D objects (Paper C).
- A novel method for assembly verification of a system of deformable 1D objects (Paper D).
- A new formulation for path optimization in the framework of quasi-static parameter optimization (Paper E).

Industrial contribution

- An efficient implementation of an accurate simulation model for deformable 1D objects well suited for real-time analysis and use in iterative algorithms.
- A new set of computational methods for design, planning and verification regarding deformable 1D objects in the virtual product realization process.
  - The methods allow for automatically finding a routed design, verifying the routed design with respect to geometrical variation and assembly and improving operations in production with respect to deformation.
  - The methods can help design and process engineers to develop a concept and to verify and improve the concept regarding deformation.
  - In the spirit of the Wingquist Laboratory implementation strategy, the methods were implemented in either demonstrator versions or commercial versions of the IPS software.

Chapter 5

Conclusions

This chapter concludes the research presented in this thesis and provides an outlook for future work.

This thesis has presented five computational methods for design, planning and verification regarding deformable 1D objects in the virtual product realization process. The first two methods are targeted at *routing design*: one method for objects that may become significantly deformed due to gravity in their routed configurations and another method for preformed hoses that are not significantly deformed. The third method is in fact a methodology for performing *variation analysis* that in particular includes a method for generating a tolerance envelope of a deformable 1D object. The fourth method is aimed at *assembly verification*, whereas the fifth method is aimed at *production planning* by performing path optimization for an industrial robot with a deformable dress pack. In summary, the methods allow for automatically finding a routing design, verifying the routing design with respect to geometrical variation and assembly and improving operations in production with respect to deformation.

The main research challenge in developing the methods was to combine simulation of deformable 1D objects with iterative algorithms for path planning, variation simulation and optimization. For this purpose, a discrete Cosserat rod model that enables efficient and accurate computations of large deformations was used. It is, however, worth pointing out that the methods could be based on a different simulation model, however it might lead to that the trade-off between computational performance and accuracy is shifted. To deal with the complexity of deformation, the path planning-related methods were separated into global path planning steps and local optimization steps.

The research results were implemented in the spirit of the Wingquist Laboratory implementation strategy. As a result, the methods are now available to the industry in either demonstrator versions or in the commercial version of the IPS software. The methods are today used at several global companies in the automotive industry, including Volvo Cars, BMW and Ford.

To conclude, important steps have been taken to strengthen the virtual product realization process. Together with existing virtual tools, the new methods can help design and process engineers develop a concept and verify and improve the concept regarding deformation. Hence, quality problems and unexpected geometrical interference between objects in both the production phase and during the life-span of the product can now to a larger extent be addressed in the concept phase. This can lead to fewer iterations between the different phases and shorter lead-times and, in the end, a product of a higher quality.

5.1 Outlook

There are several interesting topics to pursue in future research:

Geometry assurance Apart from variation analysis tools, the framework introduced in (Söderberg, Lindkvist, and Carlson 2006) consists of optimization tools for locating schemes. It could be considered to extend also these tools for deformable 1D objects.

Human assembly verification Most often the assembly of deformable 1D objects is a manual process. An interesting topic is to incorporate deformable 1D objects in a virtual human simulation tool for analyzing ergonomic aspects of human assembly.

Assembly planning If a feasible assembly operation exists, the method for assembly verification presented in Paper D outputs an assembly manipulation that takes an object to its routed configuration. Since the number of grip points that can be manipulated simultaneously is usually limited, there are combinatorial aspects to consider: How many grip points (hands) are required to perform an assembly operation? Is there a preferred order of moving the grip points?

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