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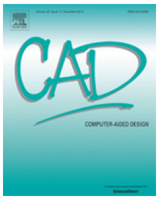

Automatic routing of flexible 1D components with functional and manufacturing constraints

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ABSTRACT

This article presents a novel and unifying method for routing of flexible one-dimensional components such as cables, hoses and pipes with geometric design constraints. A deterministic and resolution complete grid search is used to find a nominal configuration of the component that is collision-free and satisfies functional and manufacturing constraints. Local refinement is done in tandem with a computationally efficient and physically accurate simulation model based on Cosserat rod theory to ensure that the deformed configuration still satisfies functional constraints when influenced by gravity. Test results show that the method is able to solve industrial scenarios involving complex geometries and real constraints with different objectives in mere seconds.

1. Introduction

1.1. Background

In the early design phase of a product, the competition for the free design space is tough between different components. For example, the automotive industry of today is focusing on electrified and hybrid solutions, where often both conventional combustion engines and battery supplied electrical engines need to fit in an already densely packed vehicle. The placement of each component must be evaluated with respect to geometric interference with other disciplines and their components.

Specifically, flexible 1D components such as pipes, tubes, hoses and electric cables need to be routed as efficiently as possible, while still respecting functional and manufacturing constraints and requirements. Manufacturing constraints are typically imposed by process limitations and design limits, e.g. a pipe can only be pre-bent by a machine with a certain bending radius and a required straight clamping length in between bends. Functional constraints can be clearance to the surrounding obstacles, stress limits or design requirements for the component to function, e.g. the bending radius of a hose may impact the flow of the contained fluid. If there are several feasible design alternatives at hand, then one usually wants the one that is optimal with respect to material consumption (routing length), manufacturing cost (preformation) and gives preference to occupation of certain regions of space (placement).

It is of high industrial impact if a flexible 1D component can be routed by means of virtual methods already in early design phases (see Fig. 1).

1.2. Routing of flexible 1D components

A *flexible 1D component* is characterized as a slender object in $\mathbb{R}^3$ where one dimension (the length) is significantly larger than the other two (the cross section) and that exhibits an elastic behaviour. It could for instance be a rubber hose, an electric cable or a plastic or steel pipe.

Let q denote the *configuration* of a flexible 1D component and $\mathcal{S}(q) \subset \mathbb{R}^3$ its corresponding volumetric shape. Also, let $\mathcal{W} \subset \mathbb{R}^3$ denote the surrounding obstacles. A configuration is said to be collision-free if $\mathcal{S}(q) \cap \mathcal{W} = \emptyset$.

Routing of flexible 1D components amounts to finding a 'good' configuration of a component in static mechanical equilibrium that satisfies geometric design constraints inherited from both manufacturing limitations and functional requirements. The influence of gravity makes this a tremendously hard task. Therefore, in a segregated approach, the task can be separated into two procedures:

Nominal routing. Nominal routing is the task of finding a 'good' nominal configuration q_0 that (1) connects two connection points

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Fig. 1. Assembly of a high-voltage power cable in a hybrid car. © 2014, Volvo Car Corporation.

Q_S and Q_G, (2) is collision-free and (3) is feasible with respect to a set of geometric functional and manufacturing constraints of the form $h_m(q_0) \geq 0$—or reporting that no such configuration exists. The nominal configuration q_0 represents the manufactured[1] component at rest. A 'good' configuration is usually characterized as the minimizer of a cost functional related to component length and placement.

Local refinement. When a component with a nominal configuration q_0 is held at Q_S and Q_G and subjected to gravity, it assumes a configuration q in static mechanical equilibrium. Local refinement is the task of ensuring that the deformed configuration q of the flexible component is still 'good', collision-free and feasible with respect to a set of geometric functional constraints of the form $h_f(q) \geq 0$.

1.3. Related work

Extensive research has been done in the field of routing of flexible 1D components; specialized engineering methods have been derived from motion planning techniques and tailored for different component types and objectives.

Specialized hose, cable and pipe routing methods can be categorized into cell-decomposition methods [1,2], graph-based network optimization techniques [3,4] and heuristic algorithms [5]. The aim is usually to generate schematic Manhattan-style layouts in, for instance, plants and ships using as few turns as possible or following geodesic lines on, for instance, aero-engine surfaces. Engineering methods for routing electrical cables have been developed for different scenarios [6]. Channel routing algorithms have been developed for automated design of circuit layouts [7]. In power cable routing, macro-scale methods are used to optimize routes with respect to terrain information [8]. Also, genetic algorithms have been applied in some extent to solve the problem [9].

From a motion planning perspective, nominal routing of a slender component with a constant cross section profile in $\mathbb{R}^3$ can be interpreted as the problem of finding a collision free motion for a slice of the component cross section subject to curvature constraints in the Special Euclidean Group SE(3).

Determining the existence of a collision-free trajectory has proven to be NP complete for the general motion planning problem [10]. Since complete algorithms are of little industrial relevance because they are too slow, different sampling based techniques trading completeness for speed and simplicity have gained much interest. Probabilistic complete methods such as the Probabilistic Roadmap Method (PRM, [11,12]) and Rapidly-Exploring Random Trees (RRT, [13]), are capable of solving problems with many degrees of freedom. Deterministic and resolution complete methods solve the problem in finite time with a sufficiently fine resolution [14,15]. The relationship between deterministic grid search and probabilistic sampling methods is described in [16]. Dynamic planning methods that incrementally improve upon suboptimal solutions given updated information about the problem or limited computation time have been developed [17]. In *non holonomic motion planning*, differential constraints usually reduce the controllable degrees of freedom to fewer than the state space dimension. Analytical methods have been derived for car-like vehicles in 2D in [18,19]. PRM and RRT based methods have been adapted to different under actuated robots in the presence of obstacles; [20–23] implemented deterministic space-filling trees suited for this type of motion planning. Specifically, methods for routing of steerable needles with curvature constraints have been presented in [24,25]. For good and comprehensive overviews on motion planning, the reader is encouraged to read [26–29].

Adding the requirement that the component must also be in static mechanical equilibrium makes the motion planning tremendously more difficult; Incorporating a simulation model in a routing algorithm is very expensive due to the problem's computational complexity. Also, a flexible component can have infinitely many configurations corresponding to the same boundary conditions. Motion planning algorithms for linear deformable objects, most notably in [30–33], have been developed with a focus on verifying the existence of an assembly operation rather than optimizing the design of the intended target configuration. However, no deterministic grid search has been coupled to a simulation model for routing with both manufacturing and functional constraints. In separating the problem into a nominal routing step and a local refinement step, routing of flexible objects can be achieved with both high resolution and physically accurate deformations.

1.4. Scope

This article presents a novel and unifying method for routing of flexible one-dimensional components with geometric design constraints. The proposed method combines a deterministic and resolution complete grid search with a local optimization algorithm coupled to a computationally efficient and physically accurate simulation model.

An overview of the method framework is given in Section 2. In Sections 3 and 4 we formally state and present solution methods for the nominal routing and local refinement problems respectively. Test results are presented in Section 5 and our findings are concluded in Section 6.

2. Method overview

Our proposed method solves the nominal routing problem and the local refinement problem in a closed loop framework as illustrated in Fig. 2.

The `NominalRouter` algorithm seeks a nominal configuration q_0 between Q_S and Q_G that is collision-free, feasible with respect to geometric functional and manufacturing constraints $h_m \geq 0$ and favourable with respect to a given cost functional. A set of routing parameters dictate the quality and the properties of the configuration.

If a solution is found, it may serve as the initial and (optionally) as the nominal configuration in a simulation model of the component. The `LocalRefiner` algorithm attempts to ensure that the deformed configuration q is still collision-free, feasible with respect to the geometric functional constraints $h_f \geq 0$ and

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[1] Nominal configurations are typically realized through piecewise bending of pipes, moulding of hoses and clip attachment and/or taping of electric cables respectively.