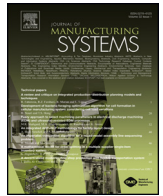




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Technical paper

Automatic assembly path planning for wiring harness installations

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ABSTRACT

The automotive industry of today is becoming more focused on electrified and hybrid solutions, where both conventional combustion engines and battery supplied electrical engines need to fit in an already densely packed vehicle. Many quality problems are related to flexible parts. In particular, the assembly of electric cables and wiring harnesses is difficult due to its concealed routing, multiple branching points, weights and the flexibility in the material. To avoid late detection of assembly problems, the assembly aspect must be considered early during conceptual design and production preparation with respect to both feasibility and ergonomics. Development of automatic path planning methods in virtual manufacturing tools supporting deformable parts is therefore highly motivated.

This article presents a novel method for automatically planning and finding a smooth and collision-free mounting of connectors in a wiring harness installation. Automatic path planning for deformable objects in general is widely acknowledged as a very difficult problem. To overcome this challenge, we propose a low-dimensional path planning algorithm that operates in the following way: *constraint relaxation, handle path planning, unfolding, path smoothing and handle supplementation*. The method has been implemented and successfully applied to an industrial test case.

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1. Introduction

The automotive industry of today is focusing on electrified and hybrid solutions, where both conventional combustion engines and battery supplied electrical engines need to fit in an already densely packed vehicle. The clearance of each component must be evaluated with other disciplines and their components. Studies in the automotive industry (see for example [1]) show that quality problems related to flexible parts and connecting tasks are the most critical. For example, the assembly of electric cables and wiring harnesses is tricky due to its concealed routing, multiple branching points, weights and awkward ergonomic postures. Therefore, the assembly aspect must be considered early during conceptual design with respect to both feasibility and ergonomics.

Efficient automatic path planning algorithms for rigid bodies has been successfully implemented and are now an integral part of many virtual tools (see Section 1.1). However, in assembly situations involving flexible parts it is almost always necessary to predict and utilize the flexibility of a part in order to find a feasible assembly path. Therefore, virtual manufacturing tools need to be strengthened in order to support real time simulations of flexible parts and motions. For example, in current tools flexible parts are typically

represented as rigid CAD geometries or splines that do not properly capture physical deformations [1]. Also, tools for virtual assembly training preparation would benefit from simulation of flexible parts to further decrease authoring times.

Automatic path planning for deformable objects in general is widely acknowledged as a challenging research area [15]. It involves both efficient simulation of elastic materials, fast collision-checking between non-rigid objects and path planning that utilizes the flexible structure of the material if necessary. Assuming that a wiring harness can be manipulated by moving a set of handles (grip points) in 3D space, the task considered is to find a manipulation so that a harness ends up in a desired target configuration in a *collision-free* way. Not only does the infamous curse of dimensionality in path planning make an early appearance in the number of manipulation handles – a transformation history is embedded in each state resulting in a many-to-one identification between handle positions and the actual topology of the scene. For example, a rope held by the rope ends could have a different number of knots or be tangled up around a static geometry with all states corresponding to the same rope end locations.

1.1. Related work

For a comprehensive introduction to the field of path planning, the reader is encouraged to read [2–4]. Due to the complexity of the problem (in fact, it has been proven to be PSPACE-hard for

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polyhedral objects with polyhedral obstacles, see [5]), completeness has been traded for speed and simplicity with various sampling based strategies, see [6]. Examples of such methods are the Probabilistic Roadmap Planner (PRM), see [7,8] and rapidly-exploring random trees (RRT), see [9]. High-dimensional path planning is addressed in [10]. The simulation of deformable one-dimensional objects has been carefully studied over the years; see for example [11–13]. There has been limited success in developing planners for deformable objects. A comprehensive survey of the field of path planning for deformable objects is given in [14]. Issues that arise when planning for flexible parts are highlighted in [15,16] path planning techniques are applied to untangle mathematical knots. A planner combining a sampling-based roadmap method with minimal energy curves is proposed in [17,18] suggests methods for deformable robots. In [19] a motion planner for robots to obtain different topological states of deformable linear objects is introduced and [20] finds motions with contact response to completely deformable surroundings. Automatic process planning for bending of sheet metals is covered in [21–23]. In [24], static harness configurations are evaluated with respect to variation in handle positions and automatic path planning for objects subject to variation is addressed by [25].

1.2. Scope

This article presents a novel method for automatically planning and finding a smooth and collision-free installation of a wiring harness. The method is not restricted only to wiring harnesses but can be applied to any tree-like structure of slender one-dimensional objects. In this article, such a system is modelled with Cosserat rods to ensure a geometrically exact and at the same time computationally efficient simulation. We propose a path planning algorithm that operates in the following way: *constraint relaxation, handle path planning, unfolding, path smoothing and handle supplementation*.

The article is structured as follows. In Section 2 we give a formal statement of the path planning problem we aim to solve. Section 3 provides a brief description of the rod model that we use in our simulation. The proposed method is outlined in Section 4 and evaluated in Section 5. Finally, the method is applied to an industrial scenario in Section 6 and we conclude in Section 7.

2. Problem statement

The goal of this work is to develop an automatic path planning algorithm that supports virtual tools for visualization and verification of wiring harness assembly. The path planning algorithm should seek continuous collision-free harness manipulations that do not strain the material more than necessary and at the same time avoid situations where the harness might become entangled with itself or surrounding obstacles.

Throughout this article a *harness* refers to a system of flexible segments connected without loops (see Fig. 1). Furthermore, we only treat quasi-static deformations, neglecting inertial effects in the harness when subject to manipulations. This assumption can be justified since in manual assembly situations accelerations are small. A set of manipulation *handles* can constrain the harness in some way and are physically manifested as m grip points, rigid connectors or cable clips clamped to the harness. A harness *configuration* $q = (S, c)$ is then defined as a harness with a shape $S \subset \mathbb{R}^3$ in mechanical equilibrium that satisfies the imposed *handle constraints* $c = \{c_i\}_{i=1}^m, c_i \in SE(3)^1$. A *manipulation* of the harness is a

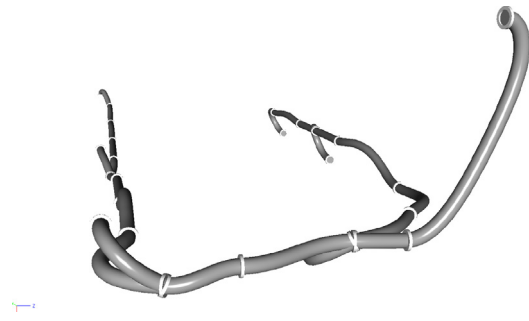


Fig. 1. A wiring harness.

synchronization of prescribed handle paths, i.e. rigid constraint motions parametrized by time t for each handle; $t \mapsto c_i(t)$.

Given an initial stress free harness configuration $q_0 = (S_0, c_0)$, possibly originating from a 2D build board layout, at a safe distance from the surrounding U , the task is to find a manipulation that transforms the harness into a given target configuration $q_T = (S_T, c_T)$, known from the design, without colliding with any obstacles, i.e. intersecting with U (see Fig. 2). Note that what makes this hard is that there could be a many-to-one correspondence between harness configurations and manipulation handle constraints – a transformation history is embedded in each state. This means that even if we find a collision-free manipulation that ends at c_T , the configuration shape S that we arrive at might not be topologically consistent with the designed target configuration shape S_T . Also, the number of degrees of freedom might become large for a wiring harness with several branches, break-outs and connectors.

The requirements on our path planning algorithm disqualify the path planning algorithms mentioned in Section 1.1. Instead we propose a path planning algorithm that utilizes contact handling and operates in a low-dimensional configuration space. Also, our method ensures that the correct configuration is entered by adding one or several supplementary handles to the harness layout (see Section 4.4).

3. Simulation model

To allow for a proper coupling with a path planning algorithm, our harness simulation model must both account for large deformations and at the same time be computationally efficient. Geometrically exact Cosserat rods (see [13]) are gaining widespread popularity for exactly those reasons and hence we chose to use them here.

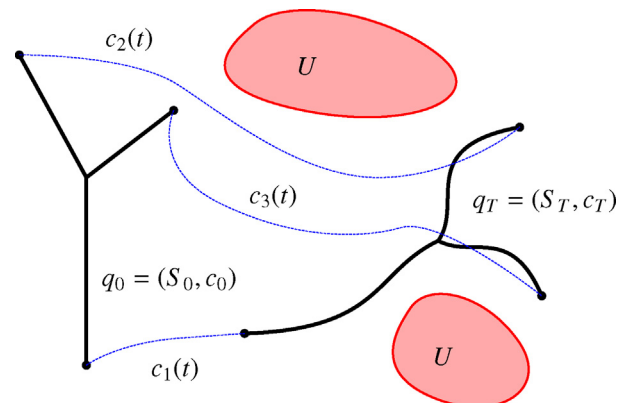


Fig. 2. A (collision-free) harness manipulation. The harness configuration $q(t) = (S(t), c(t))$ satisfies the handle constraints $c = \{c_i(t)\}$ at each time instant t .

¹ $SE(3)$ is the Special Euclidean group of dimension 3, describing all possible rigid body positions and orientations in \mathbb{R}^3 .

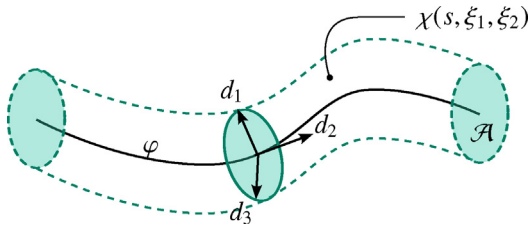


Fig. 3. The framed curve kinematics of a rod model.

3.1. Kinematics

A cable segment can express large overall deformations although locally the stresses and strains remain small. Under the assumption that the cross section always remains planar and rigid, the kinematics of an anisotropic cable are completely captured by a one-dimensional structure curve. An *extensible Cosserat rod* of undeformed length L is a framed curve parametrized by arc length s ,

$$[0, L] \ni s \mapsto (\varphi(s), R(s)) \in \text{SE}(3) = \mathbb{R}^3 \times \text{SO}(3). \quad (1)$$

φ is the *center curve* of the rod piercing the centroids of the cross section along the rod and $R(s) = (d_1, d_2, d_3)$ describes the cross section orientation; d_1 and d_2 are directors in the cross section plane and $d_3 = d_1 \times d_2$ is the director orthogonal to the cross section (see Fig. 3). Any material point in the undeformed rod is then uniquely identified in the deformed rod by the deformation mapping $\chi : [0, L] \times \mathcal{A} \mapsto \mathbb{R}^3$,

$$\chi(s, \xi_1, \xi_2) = \varphi(s) + \xi_1 \cdot d_1(s) + \xi_2 \cdot d_2(s), \quad (2)$$

where $\mathcal{A} \subset \mathbb{R}^2$ is the cross section domain.

3.2. Boundary conditions

Boundary conditions are imposed on the rod by the manipulation handles together with the branch break-outs and are realized by subsequent elimination of degrees of freedom in the discrete rod model. At an arc length position s , a rod can be constrained either to a point; $(\varphi(s)) \equiv c_\varphi$, to a point and a material direction; $(\varphi(s), d_3(s)) \equiv (c_\varphi, c_t)$, or to a point and a material frame; $(\varphi(s), R(s)) \equiv (c_\varphi, c_R)$.

3.3. Static mechanical equilibrium

To find the static mechanical equilibrium one seeks a stationary point of the potential energy functional W , of which the elastic part is composed of quadratic forms in terms of frame invariant *strain measures*.

The shearing/stretching strain vector ($\Gamma = \Gamma_1, \Gamma_2, \Gamma_3$) and curvature/torsion strain vector ($\Omega = \Omega_1, \Omega_2, \Omega_3$) in material coordinates read:

$$\Gamma(s) = R(s)^T \partial_s \varphi(s) - e_3, \quad (3)$$

$$\hat{\Omega}(s) = R(s)^T \partial_s R(s). \quad (4)$$

$\Gamma_{1,2}$ are the shearing strain components in the d_1 and d_2 directions and Γ_3 is the tension strain. $\Omega_{1,2}$ are the bending curvature components and Ω_3 is the torsion. Under the assumption of a hyper-elastic constitutive relation (which can be justified since locally Γ and Ω are small), the stored shearing/stretching and bending/torsion energy densities in a deformed rod read:

$$w^\Gamma(s) = \frac{1}{2} \Gamma(s)^T K^\Gamma \Gamma(s), \quad (5)$$

$$w^\Omega(s) = \frac{1}{2} \Omega(s)^T K^\Omega \Omega(s), \quad (6)$$

for some effective stiffness tensors K^Γ and K^Ω .

The (static) mechanic equilibrium for a single rod in the presence of a gravitational force field g is found as a solution to the balance equations,

$$\partial_s(RK^\Gamma \Gamma) - K^\rho g = 0, \quad (7)$$

$$\partial_s(RK^\Omega \Omega) + \partial_s \varphi \times (RK^\Gamma \Gamma) = 0, \quad (8)$$

or equivalently (and more efficiently) as a stationary state to the total potential energy

$$\text{Minimize } W, \quad (9)$$

$$\text{where } W = \int_{s=0}^L w^\Gamma(s) + w^\Omega(s) - K^\rho g^T(\varphi(s)) ds. \quad (10)$$

An adaptive finite difference discretization of a Cosserat rod coupled with an efficient Quasi-Newton method to minimize the energy in (10) together with the complete set of boundary conditions forms the foundation of our harness simulation.

3.4. Contact forces

Essential to the path planning algorithm that we will describe in Section 4 is the contact force interaction with the surrounding U . In order to handle non-frictional contact forces, a repelling potential energy density term \tilde{w}_d as a function of the penetration depth d is added to W . Hertz contact theory [26] suggests a potential of the form $\tilde{w}_d(s) = K^c d(s)^{5/2}$. The energy minimization problem is then

$$\text{Minimize } W + \int_{s=0}^L \tilde{w}_d(s) ds. \quad (11)$$

4. Proposed method

In this section we present the proposed method in order to automatically generate collision-free manipulations to wiring harness installations. To avoid the difficulties associated with high-dimensional path planning we propose a simple and more playful approach: Given a harness mounted at its target configuration q_T (see Fig. 4(a)), imagine that we first relax all handle constraints. Then we pull out the harness from the narrow areas with a certain minimal clearance and unfold it where the free space is unrestricted. By tracing all the (free) handle movements during this process we construct a manipulation where the individual handle paths are guaranteed to be collision-free. The paths are then reversed and locally smoothed for each handle and together they constitute the solution manipulation. As a final step, contacts still present during the manipulation (if any) are resolved by attaching a set of supplementary handles to the harness layout.

4.1. Constraint relaxation

First, we identify a centrally located point² in the harness at the target configuration q_T and attach a master handle p_H to it by introducing an additional point clip (i.e. a clip constrained to a point in \mathbb{R}^3). We then relax all the other handle constraints. The harness will immediately attain a new configuration held in balance by an applied force at p_H and external contact forces from U as the original

² Such a point on the harness can for example be the graph center of the corresponding harness tree.

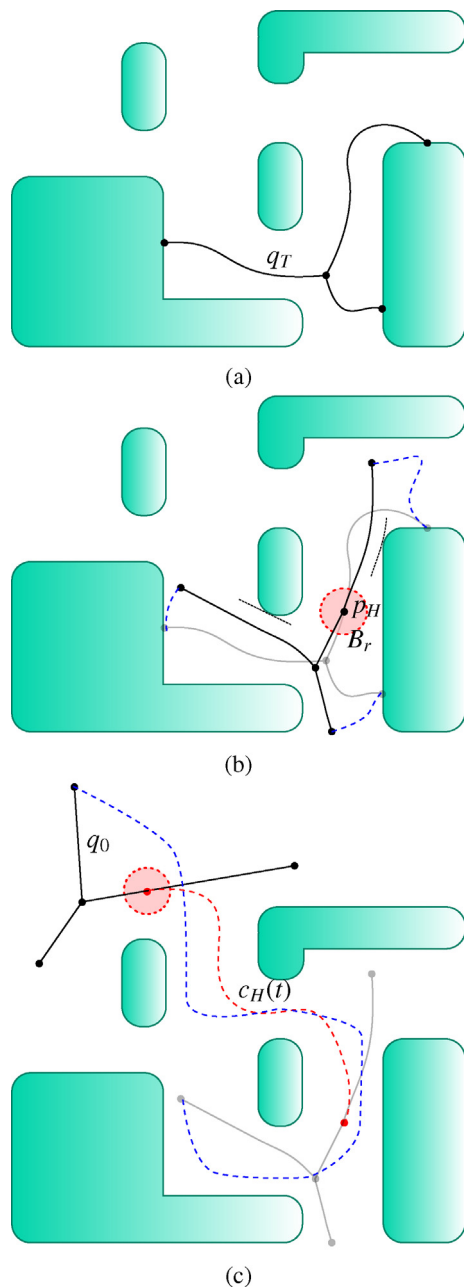


Fig. 4. Illustration of the proposed method. (a) The harness at the target configuration q_T . (b) Relaxation of all handles except for the master handle p_H . The trajectories of the handles traced out by the energy-minimization are drawn in blue. (c) Collision-free path planning for the master handle p_H to q_0 . Only the trajectory traced out by one handle is drawn.

handles are no longer held in place by c_T (see Fig. 4(b)). During this energy minimization, which for a Quasi-Newton method is composed of a series of minimizing steps in descent search directions, we carefully add the trajectories, traced out by the free-hanging handles, to the solution manipulation $t \mapsto c_S(t)$. These are certainly collision-free due to contact forces but they do not necessarily correspond to energy minima of the harness (except for the last position); when combined into a quasi-static manipulation of the harness a slightly different deformation can be attained. What matters though, is that when reversing the manipulation we still trace the same energy minimum and arrive at the configuration q_T .

To allocate suitable clearances for the subsequent smoothing steps, we keep the handle paths further away from the surrounding U by turning up the contact potential field to $\tilde{w}_{d+\delta}$ for some

parameter $\delta > 0$. Additionally, the gravitational field g is removed, since it highly influences the elastic response in the harness when constrained at p_H only.

4.2. Handle path planning

At this point we have a harness configuration balanced by holding the master handle p_H . The next step is to find a collision-free path c_H for a ball B_r (around the current position of p_H) out from zones of small clearance. For a large enough r , the tree structure of the harness will ensure that the entire harness passively will follow when moving p_H along c_H due to internal material forces and moments (see Fig. 4(c)). To generate c_H we apply a standard two-step path planning procedure in \mathbb{R}^3 . First, we conduct a local search in order to maximize clearance until B_r can fit without intersecting U . We then employ a standard A^* search finding the shortest collision-free path for the ball on a resolution complete grid in \mathbb{R}^3 . As in Section 4.1, the trajectories of the free handles are stored and appended to the solution $t \mapsto c_S(t)$.

4.3. Unfolding

Close to the configuration q_0 the harness is finally unfolded. Even though the untying of knots is a delicate research problem in itself (see [14]), we assume that our harness can be untangled with a simple stiffening procedure where we gradually increase the stiffness matrices K^T and K^Ω of the cable segments from the handle centre point and out. The motivation for this simple step is that we do not model friction, q_0 is far away from U and the harness has a tree structure. As before, the trajectories of the free handles are stored and appended to the solution $t \mapsto c_S(t)$.

4.4. Path smoothing

In the final step, we reverse the solution c_S so that we now have a manipulation starting in c_0 and ending at c_T . Also, the gravity field g is turned on and the master handle p_H is removed. The quasi-static deformations and contact forces in the previous operations have most likely generated handle paths of discontinuous curvature and that are close to the surrounding U . We therefore employ a simple smoothing procedure where we locally adjust each handle path by reducing it in a way so that the clearance is increased and the curvature is smoothed. The paths are kept synchronized by velocity tuning.

4.5. Handle supplementation

Finally, when applying the smoothed manipulation to the harness with gravitational influence, contacts with the surrounding U could occur. These are resolved by detecting the set of points in contact on the harness and attach supplementary handles. Assume for example that the first contact occurs at arc length s on a harness

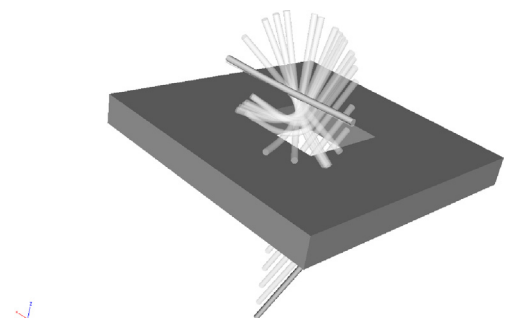


Fig. 5. A single segment harness fitted through a squared hole.

segment. To avoid the contact, the raw unprocessed solution manipulation from the steps in Sections 4.1–4.3 can be re-evaluated and used to trace out a collision-free path for a handle located at s . After having added a sufficient number of supplementary handles along the harness, we arrive at a collision-free manipulation. Similarly, the smoothing operation and the addition of the gravity field could cause the attained target configuration after manipulation to be topologically inconsistent with the intended configuration shape S_T . This is also resolved by adding supplementary handles.

Algorithm 4.1. Pseudo code of the algorithm.

```

 $H = \{p_1, p_2, \dots, p_N\}$  // The initial set of grip handles
solveForEquilibrium( $H$ )
enableContactHandling( $U, \delta$ )
 $p_H = \text{findMasterHandle}()$ 
addHandle( $p_H$ )
loop
   $S = \emptyset$ 
  for  $i = 1$  to  $|H|$  do
    removeHandle( $h_i$ )
  end for
  disableGravity()
   $S \leftarrow \text{solveForEquilibrium}(p_H)$ 
   $S_0 \leftarrow \text{pathPlanEscapeR3}(p_H, r)$ 
  if  $S_0 = \emptyset$  then
    return false // A solution could not be found
  end if
  for  $i = 1$  to  $|H|$  do
     $S_i \leftarrow \text{smoothAndReversePath}(S_i)$ 
  end for
  removeHandle( $p_H$ )
  for  $i = 1$  to  $|H|$  do
    addHandle( $p_i$ )
  end for
  enableGravity()
   $C \leftarrow \text{resolveCollisions}(S)$ 
  if  $C = \emptyset$  then
    return true //  $S$  is the solution manipulation
  end if
   $H \leftarrow H \cup C$ 
end loop

```

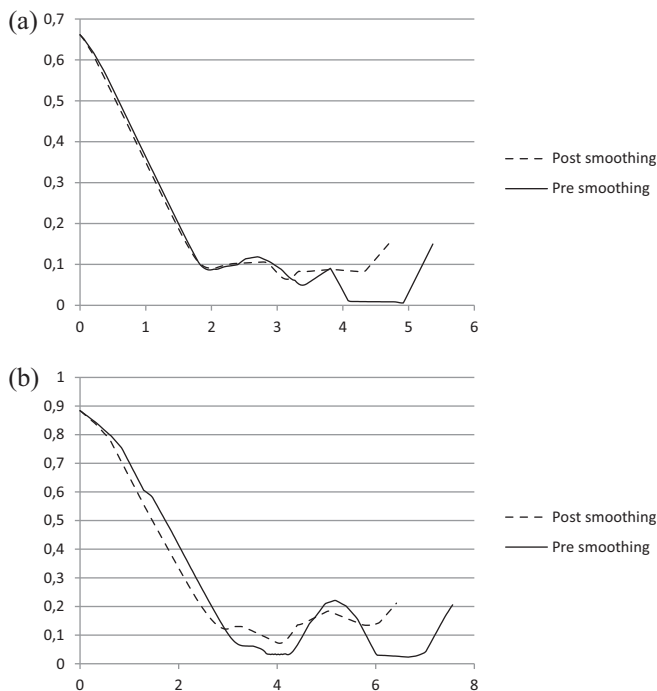
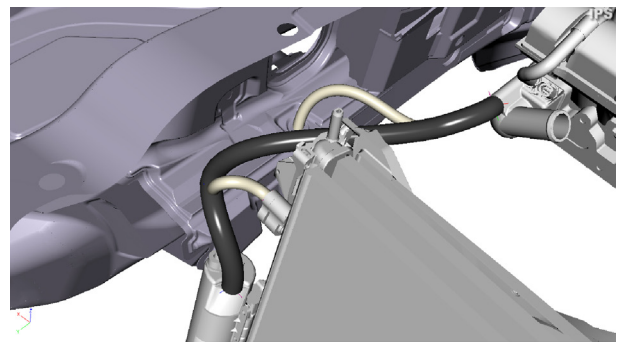
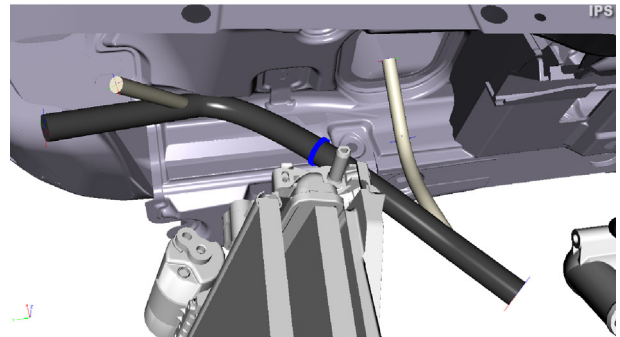


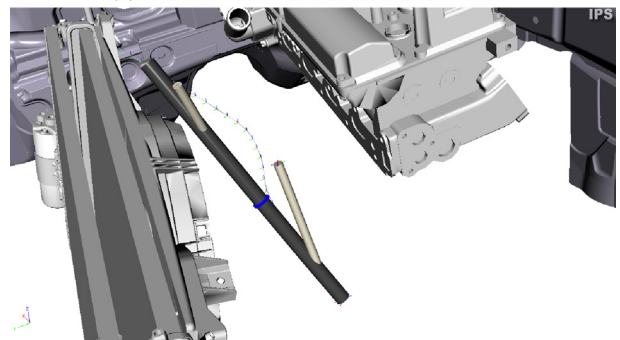
Fig. 6. Clearance between the harness and the surrounding during the solution manipulation. Note that the smoothed path is shorter and therefore reaches the target earlier. (a) $r = 30$ mm, $\delta = 10$ mm. Note: y-axis in plot is clearance in unit [m] and x-axis in plot is time in unit [s]. (b) $r = 30$ mm, $\delta = 30$ mm. Note: y-axis in plot is clearance in unit [m] and x-axis in plot is time in unit [s].



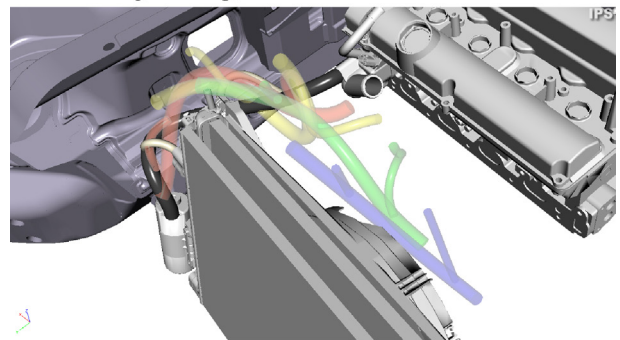
(a) The designed target configuration q_T .



(b) The harness after constraint relaxation.



(c) Path planning of the master handle out to the initial undeformed configuration q_0 .



(d) Snapshots of the harness subject to the collision-free solution manipulation.

Fig. 7. The industrial test case. (a) The designed target configuration q_T . (b) The harness after constraint relaxation. (c) Path planning of the master handle out to the initial undeformed configuration q_0 . (d) Snapshots of the harness subject to the collision-free solution manipulation.

5. Results

Crucial to the behaviour of the method are the algorithmic parameters δ and r , where δ is the support increment of the contact

potential $\tilde{w}_{d+\delta}$ (3.4) and r is the ball radius when finding a collision-free path for the master handle p_H (4.2). Also, the smoothing of the handle paths (4.4) influences the solution.

Fig. 5 illustrates a simple test scenario, where a wiring harness consisting of one single segment with a cross section radius of 20 mm is to be installed through a square-shaped hole. The harness shape is captured at various times during the manipulation at hand after the unfolding stage (Section 4.3) of the algorithm. The minimum clearance between the harness and the surrounding is plotted in Fig. 6 for different values of δ and r before and after smoothing. The algorithm finds a feasible solution and as expected the smoothing step straightens out the path and pushes it further away from the surrounding.

6. Industrial test case

The method has been implemented in industrial path solutions [27], a software for virtual assembly verification and optimization. The method was applied to the industrial test case illustrated in Fig. 7. A wiring harness of length 400 mm and radius 12 mm with two break-outs is to be connected to the inside of the engine compartment of a car. We use our planning method in order to verify that there is a collision-free path connecting the harness at the desired design configuration. The detailed surrounding contains components that could cause interference when manipulating the harness in the narrow areas. As shown in the picture, our planner finds a feasible manipulation for a contact potential parameter δ set to 10 mm and a master handle ball radius r set to 20 mm without using any supplementary handles after the final smoothing step. The total computation time of the planning algorithm was 10 minutes.

7. Conclusions

This article has introduced a novel method for finding collision-free manipulations of wiring harnesses from an initial to a target configuration. The method avoids the problems associated with high-dimensional path planning and utilizes internal forces and moments in the harness as the main component for computing collision-free manipulator handle trajectories. The wiring harness was modelled as an interconnected system of Cosserat rods to ensure a physically reliable and computationally efficient simulation, although one should note that the method is not dependent on the choice of underlying simulation model. The method was successfully applied to an industrial test case with high detail in surrounding tessellated geometry with good computation speed.

Future work could expand on the ideas presented in this article. For instance, how should the handle supplementation process be done with ergonomics in mind: in which order should handles be added and how many handle paths can be synchronized at once in a manipulation? Also, this article assumes that any contact between the harness and the surrounding renders a manipulation infeasible. Cases when a small amount of contact is acceptable and how such criteria would be defined are interesting topics for future investigation.

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