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Identification of material parameters of complex cables from scanned 3D shapes

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Abstract

Simulation of flexible components is becoming an integral part of virtual product design. However, for a simulation model to predict physically correct deformations, it is crucial that the material parameters are authentic. Conventional methods to acquire these parameters involve extensive force-displacement measurements, which may be unpractical or too expensive to perform. We propose an alternative method to identify the material parameters of a flexible one-dimensional component, such as a cable or a hose, from a scanned set of deformed reference shapes. The method finds the model parameters that give the best geometric fit between the model and the reference shapes.

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Keywords: Cable simulation, parameter estimation, point clouds, 3D scanning, geometric fitting

1. Introduction

Simulation of flexible components is becoming an integral part of the virtual product design process. Early knowledge about the elastic behaviour of a component can help modify the design in order to prevent wear and interference with other disciplines. Modelling of cables are of particular importance, since they are complex one-dimensional structures that usually exhibit large deformations and are often attributed to product failure [1,2].

For a simulation model to predict physically correct deformations it is crucial that model parameters such as stiffness in different material directions and density are authentic. Unfortunately, this information cannot always be acquired from the supplier of the cable. The conventional procedure to estimate stiffness parameters is to perform isolated force-displacement measurement tests that oftentimes involve heavy, and expensive, machinery. In many applications, it is not even feasible to set up these kinds of measurements. A tell-tale example is a dress pack mounted on an industrial robot; isolated flexural tests are hard to accomplish since the cable is restricted to the kinematics of the robot and might even break.

As an alternative, we propose a novel method, dubbed `Scan2Flex`, for calibrating a quasi-static cable simulation model by scanning a set of reference shapes assumed by the cable. The method finds the model parameters that give the best geometric fit between the model and the reference shapes.

1.1. Outline

The paper is structured as follows. Section 2 introduces a cable simulation model and how its material parameters can be identified by measurements. An overview of `Scan2Flex` is given in Section 3. Section 4 covers the process of generating a set of reference shapes by scanning the cable in distinctive poses. Section 5 describes the how to estimate model parameters by geometric fitting w.r.t. the reference shapes. The method is applied to an industrial scenario and results are presented in Section 6. We conclude our findings in Section 7 together with a future outlook.

2. Cable simulation and measurements

A cable is characterized as a slender elastic object in $\mathbb{R}^3$ where one dimension (the length) is significantly larger than the other two (the cross section). Under the assumption that the cross section always remains planar and rigid, a cable can be modelled as a *Cosserat rod*.

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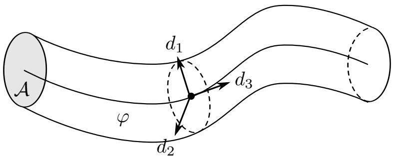

Fig. 1: A rod representation of a cable.

2.1. Cosserat rod theory

Cosserat rod theory [3] accounts for large elastic deformations in the form of both shearing, stretching, bending and torsion. The kinematics of a Cosserat rod of length L are captured in an arc length parameterized framed curve in SE(3) = $\mathbb{R}^3 \times$ SO(3);

$$q : [0, L] \ni s \mapsto (\varphi(s), R(s)) \in \mathrm{SE}(3). \tag{1}$$

Here, $R = (d_1, d_2, d_3) \in \mathrm{SO}(3)$ describes the evolution of the cross section orientation along the center curve φ. The shearing/stretching strain vector Γ and curvature/torsion strain vector Ω are defined in material coordinates as

$$\begin{aligned} \Gamma(s) &= R(s)^T(\partial_s\varphi(s) - d_3(s)) \\ \hat{\Omega}(s) &= R(s)^T\partial_s R(s). \end{aligned} \tag{2}$$

$\Gamma_{1/2}$ are the shearing strain components w.r.t $d_{1/2}$ and Γ_3 is the tensile strain w.r.t d_3. $\Omega_{1/2}$ are the bending curvature strain components w.r.t to $d_{1/2}$ and Ω_3 is the torsion strain w.r.t d_3.

With a hyper-elastic constitutive law, the force and moment vectors f and m are related to the strains as follows:

$$\begin{aligned} f(s) &= R(s)K_\Gamma(\Gamma(s) - \Gamma_0(s)) \\ m(s) &= R(s)K_\Omega(\Omega(s) - \Omega_0(s)), \end{aligned} \tag{3}$$

where the effective stiffness matrices

$$K_\Gamma = \begin{pmatrix} k_{GA1} & 0 & 0 \\ 0 & k_{GA2} & 0 \\ 0 & 0 & k_{EA} \end{pmatrix}, \quad K_\Omega = \begin{pmatrix} k_{EI1} & 0 & 0 \\ 0 & k_{EI2} & 0 \\ 0 & 0 & k_{GJ} \end{pmatrix}. \tag{4}$$

$k_{GA1/2}$ are the shearing stiffness components w.r.t $d_{1/2}$ and k_{EA} is the tensile stiffness w.r.t d_3, whereas $k_{EI1/2}$ are the bending stiffness components w.r.t $d_{1/2}$ and k_{GJ} is the torsional stiffness w.r.t d_3. Γ_0 and Ω_0 are nominal strain vectors representing predeformation in the model.

In static mechanical equilibrium, together with boundary conditions, the force and moment balance equations hold,

$$\begin{aligned} \partial_s f(s) + k_{\rho A} g &= 0 \\ \partial_s m(s) + \partial_s\varphi(s) \times f(s) &= 0, \end{aligned} \tag{5}$$

where $k_{\rho A}$ is the length density and where we have assumed that the only external load is due to the gravity field g.

If the cable material is homogeneous or has a perfect wire rope-like structure without internal friction, the effective stiffness parameters can sometimes be derived analytically [4–6]. For most cables in industry such assumptions cannot be made and the material parameters need to be estimated in measurement tests.

2.2. Measurement tests

In order to estimate the material parameters of a cable, various measurement tests can be derived from Eq. 5 as special cases that isolate the estimation of each material parameter. Each stiffness parameter is typically estimated by varying an applied force or moment, measuring the corresponding strain and fitting a straight line to the obtained force-displacement or moment-twist curve [7]. Typical measurement tests (for different stiffness parameters) found in engineering handbooks are the *tensile test* (k_{EA}), the *torsional test* (k_{GJ}) and the *three point bending test* ($k_{EI1/2}$). These tests neglect the influence of gravity altogether and require that the applied force or moment is measured. When force and moment boundary conditions are not known and the deformation can only be measured from a limited set of feasible poses, the tests cannot be realized in practice.

2.3. Geometric fitting

One way to identify material parameters from deformation is to seek the parameters that provide the best geometric fit between the simulation model and a set of reference shapes assumed by the cable. If the model is accurate and the geometric boundary conditions (e.g. $q(0) = q_0$ and $q(L) = q_L$) are given and the different strain types are encoded in the reference shapes, this process can produce material parameters that predict correct *deformations*.

There is however one caveat: By inspection of the balance equations (Eqs. 5) and the constitutive relations (Eq. 3), we observe that solutions to the systems in terms of strains are invariant to scaling of the material parameters.[1] Thus, if we want material parameters that produce correct *forces and moments*, one material parameter must be explicitly known. Most often, the length density $k_{\rho A}$ is either known from the supplier or is easily measured.

As a simple example, consider a cantilever cable, i.e. a free-hanging horizontal cable attached in one end, subject to its own weight. If $k_{\rho A}$ is known, $k_{EI1/2}$ uniquely determine the shape of the cable in equilibrium and can be computed directly from geometric fitting of the free end position. In some sense, the known gravitational force $k_{\rho A} g$ here plays the role of the known external force in e.g. a three point bending test. In practice, it is not always feasible to perform this particular test and the obtainable reference shapes usually encode a combination of bending and torsion.

2.4. Errors and uncertainties

Discrepancy between the simulation model and the cable is ever present due to mainly approximations in the model and measurement errors, This prevents us from achieving a perfect geometric fit between the model and the reference shapes.

[1]This means that if e.g. a hyper-elastic cable is placed in outer space, we will not be able to visually detect whether it is stiff or soft from its deformed shape alone. In a gravity field, the scale of the stiffness parameters is uniquely determined by e.g. knowing the mass of the cable.

Model approximations. A one-dimensional rod structure does not capture higher-order deformations, such as warping of the cross section. Furthermore, non-linear elasticity and plasticity usually occur in complex cables due to friction, and breakdown of the cross section is not accounted for in the model. Also, as with all simulation models, errors are introduced when discretizing the model.

Measurement errors. Noise in scan data causes errors in the reference shapes and the geometric boundary conditions which can lead to significant estimation errors in the material parameters. In fact, for the cantilever test it can be shown that for a normal distributed error Δu in measured vertical displacement u, the relative error $\Delta k_{EI}/k_{EI}$ in the estimation of k_{EI} is proportional to $k_{EI}/|gk_{\rho A}|$. Hence, for stiff cables where the bending stiffness is much larger, in some sense, than the weight per meter cable, small measurement errors can propagate to large estimation errors.

2.5. Model implementation

For an efficient implementation of the Cosserat rod model to couple with an iterative data fitting algorithm, we first write the total potential energy of the rod as

$$W = \int_{s=0}^{L} \Big\{ (\Gamma - \Gamma_0)^T K_\Gamma (\Gamma - \Gamma_0) + (\Omega - \Omega_0)^T K_\Omega (\Omega - \Omega_0) - k_{\rho A} g^T \varphi \Big\} ds. \tag{6}$$

By the Hamiltonian principle, solving Eqs. 5 is equivalent to finding a stationary point to the potential energy of the system,

$$\delta W = 0, \tag{7}$$

which is computationally more efficient. In order to do so, Eq. 6 is discretized by expressing the discrete strains as non-linear geometric finite differences and analytical expressions are derived for the gradient of the discrete energy functional (see e.g. [8,9] for details concerning efficient implementations of Cosserat rod models). A Quasi-Newton minimization method (e.g. [10]) can then be employed in order to efficiently find a static equilibrium satisfying Eq. 7.

3. Method overview

The first step in `Scan2Flex` is to generate a set of reference shapes by scanning the cable in a series of distinctive poses. The reference shapes are compactly stored as center curves extracted from the scan data with some help from user input. The simulation model of the cable is then initialized with known parameter values supplied by the user. The parameter estimation procedure finds the unknown parameters that give the best geometric fit between the model and the reference shapes. The estimated parameters are finally examined in a validation test. If deemed inaccurate, it is necessary to either tweak the estimation procedure or restart the method by generating new reference shapes. Fig. 2 shows a schematic view of the process.

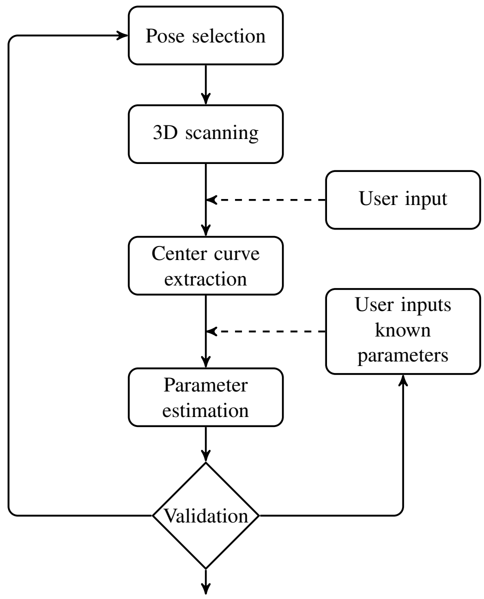

Fig. 2: A schematic view of the `Scan2Flex` method.

4. Reference shape generation

Let $S \subset \mathbb{R}^3$ denote the deformed shape of a cable and let q_0 and $q_L \in \mathrm{SE}(3)$ denote the cable end positions when held fixed in space (i.e. the imposed geometric boundary conditions). Together they form a *cable pose*.

4.1. Pose selection

Since it is desired that the reference shapes encode the material characteristics of the cable, a crucial step is to choose which poses to use. This decision of course depends on which poses are feasible for the cable, however some general guidelines can still be given.

As noted in Section 2.3, if the length density $k_{\rho A}$ is known, gravity acts as a key that allows for the stiffness parameters to be found. At least one of the chosen poses should display a significant influence of gravity, i.e. such that gravity causes the cable to sag considerably under its own weight.

To capture the interaction between bending stiffness $k_{EI1/2}$ and torsional stiffness k_{GJ}, it may be a good idea to choose the poses in pairs. In the first pose, the cable shape should be as relieved from torsion as possible and the second pose should be identical to the first but with induced torsion by twisting one of the ends a significant angle (e.g. 90°).

4.2. 3D scanning

When scanning the shape S of a cable in a certain pose it is important that the whole shape is captured. At the same time, it is also important that surrounding unrelated objects can be easily culled from the scan data. Amongst all the different commercial scanners available on the market, two scanners were evaluated: the budget sensor Microsoft Kinect V2 [11] and a more sophisticated handheld device from FARO [12] called Scanner Freestyle 3D. Both are depth sensors capable of generating 3D point clouds. With a superior scan accuracy of (< 1mm at a 1m distance), the FARO device was the most suitable for our experiments.

4.3. Center curve extraction

Let $P = \{p_i\}_{i=1}^N \subset \mathbb{R}^3$ denote the point cloud representation of a successfully scanned cable shape S. For an efficient evaluation of the geometric fit between P and the rod model (Section 5.2), we wish to store the reference shape on the same compact form.

The task of extracting a center curve $\bar{\varphi}$ from P is a challenging step. So called *active contour models* or *snakes* [13] is a well-known class of algorithms to find and represent spline curves in 2D or 3D data. An initial solution is required however, hence we first look for a coarse approximation of the center curve. Automatic methods to accomplish this were evaluated, but they were not robust enough w.r.t. the quality of the scanned point cloud. Instead, the user is asked to manually mark a sequence of K guiding points on the cable's surface. A spline curve $\bar{\varphi} : [0, K] \mapsto \mathbb{R}^3$ was then interpolated from the guiding points, providing a start solution for the snakes algorithm.

4.3.1. Smoothing

The idea behind active contour models (snakes) is to find a curve that minimizes some energy functional that encodes some problem dependent criteria. The energy functional E can be decomposed into an external and internal part, $E = E_{ext} + E_{int}$. The external energy E_{ext} encodes the main objective of the problem at hand and aims to push the curve inside the point cloud boundary. The internal energy E_{int} tries to enforce the curve to behave smoothly, typically by penalizing curvature. For our purpose, we used the following normalized energy terms

$$
\begin{aligned}
E_{int}(\bar{\varphi}) &= \frac{1}{Nr^2}\sum_{i=1}^{N} \|d(\bar{\varphi}, p_i) - r_i)\|^2 + E_1(\bar{\varphi}) \\
E_{ext}(\bar{\varphi}) &= \frac{1}{K-2}\sum_{k=2}^{K-1} \frac{v_{k-1}^T v_k}{\|v_{k-1}\|\|v_k\|} + E_2(\bar{\varphi}).
\end{aligned}
\tag{8}
$$

Here, r is the nominal radius supplied by the user, r_i is a radius associated to a each cloud point from the coarse approximation step. $d(\bar{\varphi}, p)$ is the closest distance between the spline and a cloud point p and $v_k = \bar{\varphi}'(k - 1/2)$ is the spline tangent. E_1 and E_2 are penalty terms included to ensure that the curve does not extend outside the point cloud and does not deviate from uniform arc length respectively.

The minimization problem is solved using the conjugate gradient method with restarts and numerical gradient evaluations. Convergence was pretty slow indicating that this is a quite tricky optimization problem.

5. Parameter estimation

The Cosserat rod model described in Section 2.1 takes as input a set of model parameters x and geometric boundary conditions q_0 and q_L and computes the deformed rod configuration $q^* = (\varphi^*, R^*)$ in static equilibrium; $(x, q_0, q_L) \mapsto q^*$.

5.1. Model parameters

The model parameters x are the different material parameters $k_{\rho A}$, $k_{GA1/2}$, k_{EA}, $k_{EI1/2}$ and k_{GJ}, the nominal cable length L and the nominal strain vectors Ω_0 and Γ_0.

We rearrange $x = (x_C, x_E)$ into known model parameters x_C supplied by the user and unknown model parameters x_E to be estimated. In the typical case, $k_{\rho A}$, L, Ω_0 and Γ_0 are known, however this cannot be assumed in general. Also, if the cable is observed to be nearly inextensible, $k_{GA1/2}$ and k_{EA} can be fixed to a large value (∼100 000 N).

5.2. The geometric fitting problem

Let $\{\bar{\varphi}_i\}_{i=1}^M$ be a set of M reference center curves generated from the previous steps and $\{q_0^{(i)}\}_{i=1}^M$ and $\{q_L^{(i)}\}_{i=1}^M$ the corresponding geometric boundary conditions. Furthermore, let Π be a given shape distance metric that measures a generalized distance between two center curves (see Section 5.2.1).

The *geometric fitting problem* is then to find the model parameters x_E that give the best fit between the model and the reference center curves $\{\bar{\varphi}_i\}_{i=1}^M$ w.r.t. Π:

$$
\begin{aligned}
\underset{x_E}{\text{minimize}} \; & \sum_{i=1}^{M} \Pi(\varphi^*(x, q_0^{(i)}, q_L^{(i)}), \bar{\varphi}_i) \\
& x = (x_E, x_C) \\
& x_E \in X,
\end{aligned}
\tag{9}
$$

where X is a user supplied range for the minimization variables x_E.

5.2.1. Shape distance metric

To measure the distance between two center curves φ and $\bar{\varphi}$, we use a point-wise integrated squared distance metric Π, calculated like so:

$$
\Pi(\varphi, \bar{\varphi}) = \frac{1}{L}\int_{s=0}^{L} \|\varphi(s) - \bar{\varphi}(s)\|^2 \, ds. \tag{10}
$$

If the tensile strain is uniform, this simple formula provides a reasonable average squared distance between two center curves. Other more sophisticated metrics could also be considered; e.g. the *Hausdorff distance* is invariant to the parameterization of the center curves but at the same time more expensive to evaluate.

5.2.2. Solving the problem

The Nelder-Mead algorithm [14] is used to solve the geometric fitting problem (Eq. 9). It is a gradient-free iterative solver for non-linear optimization problems and thus suitable for coupling with the simulation model. For an initial solution to start the algorithm, the user is asked to provide guesstimates for the unknown material parameters x_E. It should be noted, that the Nelder-Mead algorithm may not have fast convergence and may only find a local minimum.

5.3. Validation

To validate the estimated model parameters, a comparison between the calibrated model and other scanned poses of the

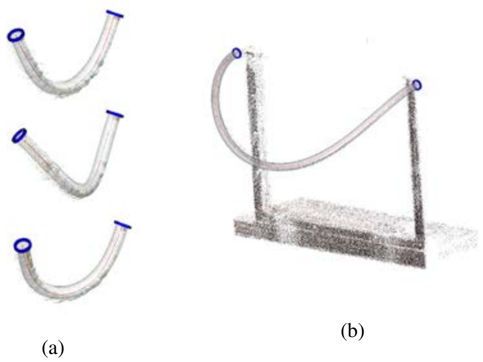

Fig. 3: The calibrated simulation model and scanned reference shapes for (a) the robot dress pack and (b) the PTFE single core cable.

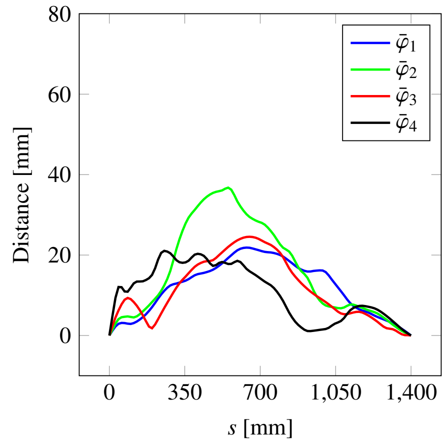

Fig. 4: The point-wise distance between center curves from a robot dress pack scanned in different poses and the best fit of a simulation model.

cable can be conducted. Also, engineering hand books can give a hint on which order of magnitude of the parameters to expect.

If the estimated model parameters seem invalid, different actions can be taken. Since solutions to the geometric fitting problem (Eq. 9) are sensitive to the initial solution, other guesstimates of x_E could be tested. If the different strain types are not properly encoded in the reference shapes or if the shapes are of bad quality they may then have to be regenerated.

There are also possible sources of error in the known parameters x_C to consider. For example, measuring the nominal length L or the inherent nominal strains Γ_0 and Ω_0 from a deformed reference shape will produce an error. If possible, these quantities should be measured by scanning the cable in a stress-free pose. Also, solutions to Eq. 9 are sensitive to the geometric boundary conditions $q_0^{(i)}$ and $q_L^{(i)}$. It is therefore important to measure the precise position of the cable ends. An alternative solution could be to let these quantities enter x_E as unknown model parameters also to be estimated.

6. Results

6.1. Physical verification

`Scan2Flex` was verified on two real-life cases: scanning a *robot dress pack* and estimating its flexural stiffness and scanning a *PTFE single core cable* and estimating its bending stiffness. The scans were performed with Microsoft Kinect and Scanner Freestyle 3D from FARO, respectively.

To determine the flexural stiffness parameters k_{EI} and k_{GJ} of the robot dress pack, three distinctive poses were selected according to the guidelines in Section 4.1; one pose without twist and two poses with $-90°$ and $90°$ twist (see Fig. 3a). This resulted in three extracted reference center curves $\bar{\varphi}_1$, $\bar{\varphi}_2$ and $\bar{\varphi}_3$. Also, a center curve $\bar{\varphi}_4$ extracted from a pose with 45° twist was used for validation. The dress pack was assumed to be inextensible and the nominal length ($L = 1.4\,\mathrm{m}$), radius ($r = 43\,\mathrm{mm}$) and length density ($k_{\rho A} = 3\,\mathrm{kg/m}$) were known. The estimated stiffness parameters were $k_{EI} = 6.47\,\mathrm{Nm}^2$ and $k_{GJ} = 33.38\,\mathrm{Nm}^2$. Fig. 4 shows the point-wise errors between the model and the center curves. The error was reasonably small compared to the dress pack dimensions and remained consistent for the validation center curve as well.

For the PTFE single core cable, a torsion-free pose was chosen so that it displayed a clear interplay between gravity and bending. The cable was considered inextensible and the length density ($k_{\rho A} = 0.336\,\mathrm{kg/m}$)and the nominal length ($L = 0.90\,\mathrm{m}$) of the cable were known. The estimated bending stiffness was $k_{EI} = 0.0419\,\mathrm{Nm}^2$. The predicted shape of the calibrated simulation model is visualized in Fig. 3b together with the scanned point cloud.

6.2. Verification by simulation

The robustness of the parameter estimation procedure was analyzed with input from a cable modelled in the simulation software IPS [15]. A simulated cable with bending stiffness $k_{EI} = 0.1\,\mathrm{Nm}^2$ and torsional stiffness $k_{GJ} = 0.25\,\mathrm{Nm}^2$ was set in distinctive poses and a reference center curve was obtained for each pose (bypassing the 3D scanning and center curve extraction steps).

In order to analyze the sensitivity w.r.t. supplied initial values, k_{EI} and k_{GJ} were treated as unknown model parameters. Initial values were systematically varied in the range of 0.01 to $100\,\mathrm{Nm}^2$, covering most of the spectrum of physically meaningful values for flexible components. The correct values $k_{EI} = 0.1\,\mathrm{Nm}^2$ and $k_{GJ} = 0.25\,\mathrm{Nm}^2$ were recovered in most cases (19 out of 25), indicating that our method is robust for finding the material parameters when the simulation model is exactly accurate. In the unsuccessful cases, the algorithm converged to other (non-physical) local minima. An experienced user would be able to identify and circumvent these solutions by visual inspection and adjusting the initial values by hand.

As noted in Section 5.3, it is crucial that the geometric boundary conditions are accurate. In order to verify this, the cable end orientations were perturbed while the unknown stiffness parameters k_{EI} and k_{GJ} were initialized to the correct values (See Fig. 5). We observe that the parameters were underestimated for all perturbations, indicating that the procedure is sensitive to the geometric boundary conditions. A possible reason for this particular behaviour could be that lower stiffness parameters are favourable in order to geometrically fit the reference shapes near the cable ends (where the deviation is most prominent).

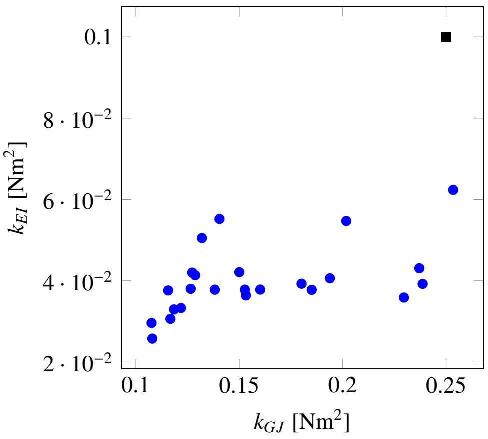

Fig. 5: The estimated values of k_{EI} and k_{GJ} (•) when the cable end orientations were randomly perturbed with an angle between $-3°$ and $3°$. The original values in the simulation model were $k_{EI} = 0.1\,\mathrm{Nm}^2$ and $k_{GJ} = 0.25\,\mathrm{Nm}^2$ (■).

Finally, as also noted in Section 5.3, estimation errors occur when pre-deformation (i.e. inherent nominal strain) is not accurately captured in the model[2]. When the nominal bending strain in the model was constant around a fixed material direction ($\Omega_0(s) = \kappa_0 e_{1/2}$ for some scalar κ_0), the correct value of Ω_0 was recovered in most cases. This suggests that, as long as the nominal strain is known to be constant and can be separated from the actual strain in the reference shapes, the method will have a good chance of estimating nominal strain parameters correctly.

7. Conclusions and outlook

We have presented a novel method, `Scan2Flex`, for calibrating a cable simulation model by scanning a set of reference shapes assumed by the cable. The method is tailored for the cases when conventional measurements are not applicable and finds the model parameters that give the best geometric fit between the model and the reference shapes. In the hands of an experienced user, who can provide accurate values for the known model parameters and good guesstimates for the unknown ones, the method is a powerful tool for estimating the material parameters of a complex cable from scan data.

Results indicate that the method can successfully produce reasonable estimates of model parameters for typical cables encountered in industry. Validation with input from a simulation model shows that the method is robust w.r.t. guesstimates of the unknown model parameters but is clearly sensitive to the accuracy of the geometric boundary conditions. Also, pre-deformation in the cable can be accounted for, either by scanning the stress-free shape or by estimation.

To extend upon this work in the future there are several possibilities:

- Perform more rigorous testing and verification with other types of cables,
- Adapt the pose selection guidelines for more specific cases, e.g. exploiting knowledge about the feasible poses of an industrial robot when estimating the material parameters of its dress pack,
- The validation of the estimated material parameters relies on user experience. This process could be made automatic,
- In the current method, the center curve extraction allows for a compact representation of the reference shape and hence an efficient evaluation of the shape distance metric. However, for lower quality point clouds this step is sometimes not robust. Hence, there is a potential benefit in skipping this step and considering the entire point cloud in each shape distance metric evaluation.

[2]Most cables in industry have pre-deformation; e.g. when cables are transported it is common to package them into coiled structures, leading to a pre-deformed circular shape

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