The International Journal of Advanced Manufacturing Technology (2018) 96:2183–2193
https://doi.org/10.1007/s00170-018-1675-9

ORIGINAL ARTICLE

Simulating robotic manipulation of cabling and interaction with surroundings

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Received: 19 August 2017 / Accepted: 25 January 2018 / Published online: 20 February 2018

Abstract
The manipulation of non-rigid parts, particularly cabling structures, such as the cable harness, raises various issues that require dealing with complex modeling. The first important issue is the prediction of the shape of flexible parts itself. Also, addressing collision detection problems is of high importance. However, both are computationally intensive problems, as well as coupled. More specifically, regarding modeling, the structure of a harness can affect the mechanics (regardless of whether it is modeled like a cable). In this paper, such phenomena have been taken into account. What is more, collision detection between cables and rigid bodies is performed, regarding a quasi-static approach. Furthermore, cable-cable interaction cases are also addressed with the herein presented algorithm. A methodology, based on the geometrical characteristics of a cable, is given, and illustration from implementation in a commercial software is discussed. The simulation of an industrial case of assembling cabling harness in automotive sector is used to prove the usability of the algorithm and the modeling.

Keywords Flexible parts handling · Harness assembly · Dual arm · Cable shape prediction · Collision avoidance · Bodies contact · Assembly parts interaction · Simulation

1 Introduction

The need for automated assembly has been increasingly presented in literature [1]. Recently, a study indicating the integration of sophisticated mathematical models that predict the shape of cables during manipulation has been published [2]. Figure 1 shows the result of such a shape prediction that has been integrated into assembly simulation, through a commercial simulation program.

However, a related research has to undergo further advances, namely, the integration of collision detection, in order for the manipulation of such a part to be more realistically simulated. In the current work, there is a discussion on the approach towards such a collision manipulation tool. This approach attempts to overcome the mechanical problem related to friction, by introducing a geometry-based methodology. The added value of the current approach is that, besides taking into account shape prediction solutions that are of higher accuracy when they are being compared to a real cabling shape [2], it also overcomes the collision manipulation non-linearities through a process simulation environment.

Prediction of shape itself, as also performed in [2] has been achieved with using higher order differential equations which can be calibrated experimentally. This has allowed modeling herein also interactions as boundary conditions in the position as well as in the inclination at the interaction points. Also, a process simulation environment was exploited to take advantage of the criteria that are mentioned in Fixed points as obstacles: extra conditions and ambiguities; knowing movement for example is a necessary piece of information to pre-calculate any potential collisions/interactions.

Furthermore, the current implementation of the methodology is in line with procedures, such as virtual commissioning, under the virtual factory concept [3]. Finally, in conjunction with a path planner (i.e., [4] or [5], for a dual-arm robot case), it will lead to an automated assembly [6].

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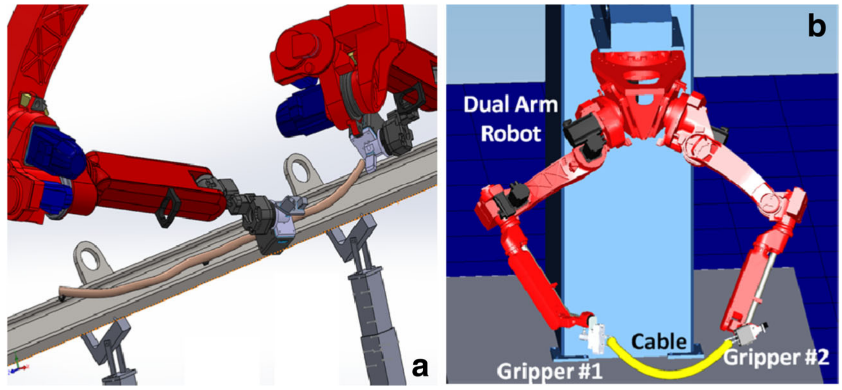


Fig. 1 The concept of automated cabling assembly (**a**) and prediction of cabling shape during robotic manipulation (**b**). Source [2]

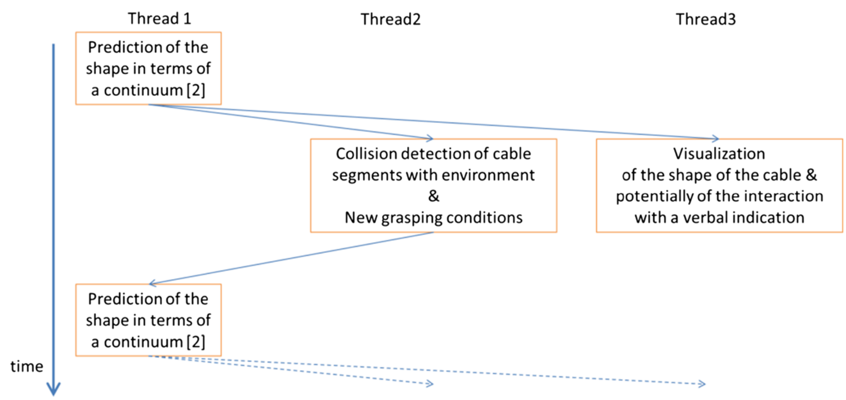


Fig. 2 Draft description of the approach as communication between three threads

1.1 Relevant work

There is a plethora of papers in literature with physics studies, based on interactions between flexible bodies [7] in robotics. Firstly, it is worth mentioning an attempt for the formulation of and solution to the inverse kinematics of a wire-driven parallel robot [8], under the assumption that there is no friction between any two colliding wires at the meeting point. Using a theoretical analysis and utilizing a six-degree-of-freedom redundant robot design as a case study, the authors were able to prove that the permission of wire collisions, compared with the collisions-free case, enabled a significantly larger workspace. What is more, there are also studies dealing with the collision detection of rigid bodies with cables [9]; the cables are being addressed as a chain of rigid segments, based on mass-spring system. Other approaches involve quasi-static Cosserat media and Kirchoff models [10], while physics engines have also included simulations of cables and rods [11]. Moreover, in the wider context of flexible materials manipulation, less physical approaches, such as Bayesian filtering, have been used [12]. Furthermore, regarding a multi-threaded version of the 1D Sweep-and-Prune Self-Collision Detection algorithm for the deforming cables algorithm, its performance has been investigated in [13]. Moreover, the cables' behavior is discussed in cases of path planning, such as in the case of multiple mobile cranes, in different kinds of applications [14].

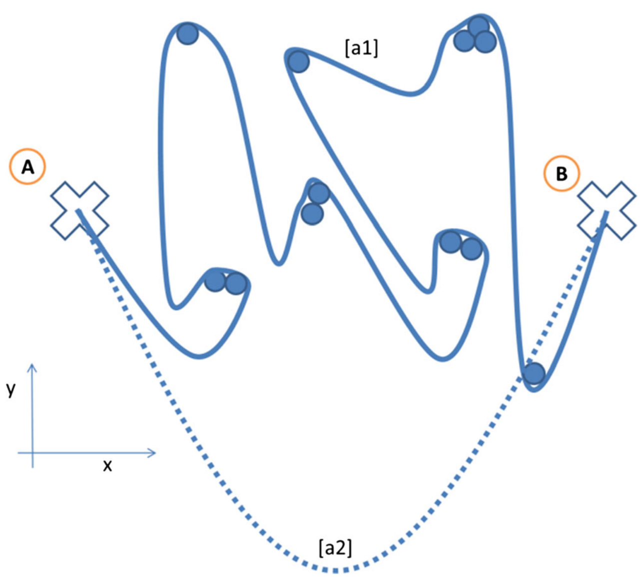


Fig. 3 Static picture of a cable grasped at two ends (dotted line) and a cable grasped at two ends and forced to be fixed at intermediate points (continuous line)

Additional studies, indicative of the significance of the generic framework of contact mechanics, in robotics-based manufacturing processes and assembly, comprise the introduction of a new theory of the contact pressure distribution and friction limit surfaces for the modeling of hemi-cylindrical soft fingertips [15]. It also refers to the development of a novel

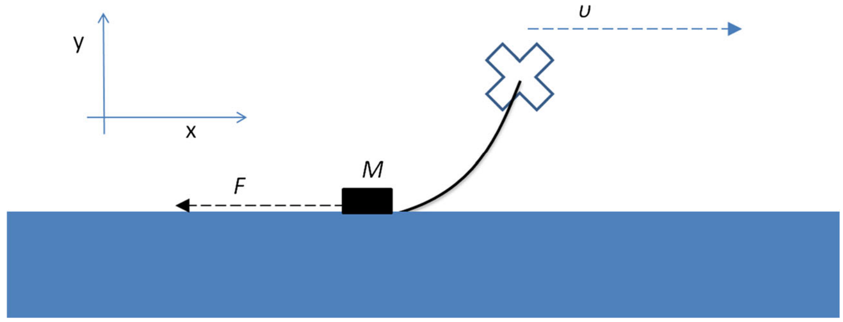


Fig. 4 Friction in contact mechanics

algorithm, in the case of walking robots [16], for the detection of motion-related state transitions in stick-slip motion.

2 Modeling approach

The approach of modeling the cable shape has been thoroughly given in [2] deriving from higher order mechanics that can encapsulate size-effects; that is, the micro-structure affecting the macro-behavior of a body [2, 17].

Moreover, the approach to predicting the collisions between the various entities (cables and a robot) is considered in terms of three threads (Fig. 2), one for predicting the shape (Mathematica kernel), given the boundary (grasping) conditions [18]; the second for re-evaluating the boundary conditions, based on the environment simulation (performed by Process Simulate); and the third one has undertaken the visualization (also performed by Process Simulate). Thus, there can be two kinds of boundary conditions (BCs):

- Related to the grippers, this kind of BC has already been taken into account in a previous work [2], in terms of both position and orientation of the gripper.
- Related to the environment, these BCs regard the case where the cable interacts with the environment.

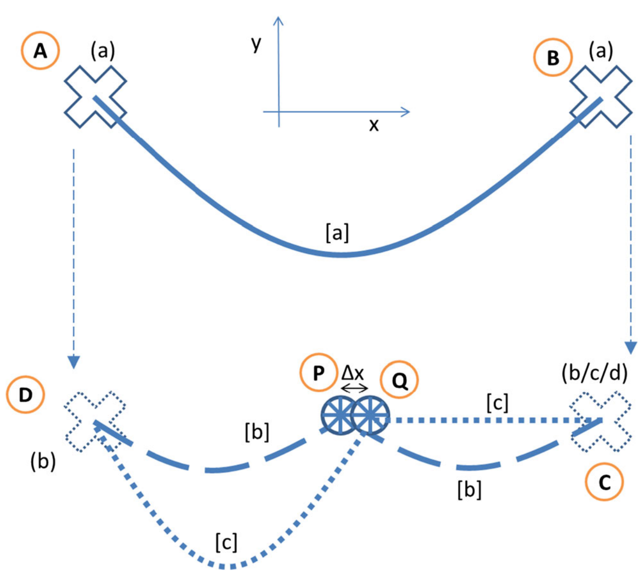


Fig. 5 Example of a contact of type FØ (without any friction)

It has to be noted here that the cable may interact with itself, namely, through curling and twisting, causing two different points of the cable (denoted by different values of the physical parameter *s* [2]) to collide. Furthermore, during running, the thread estimates the collisions' positions while the cable is segmented into parts for the easier manipulation of the collision points.

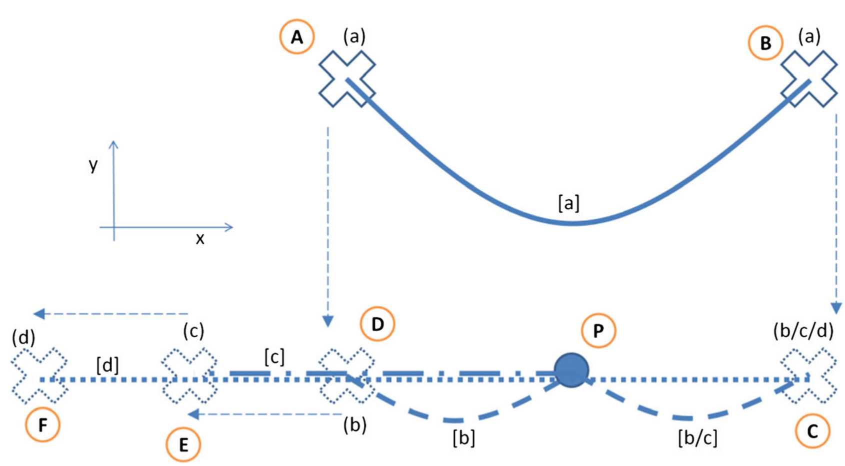


Fig. 6 F∞ contact case indicating distance criterion

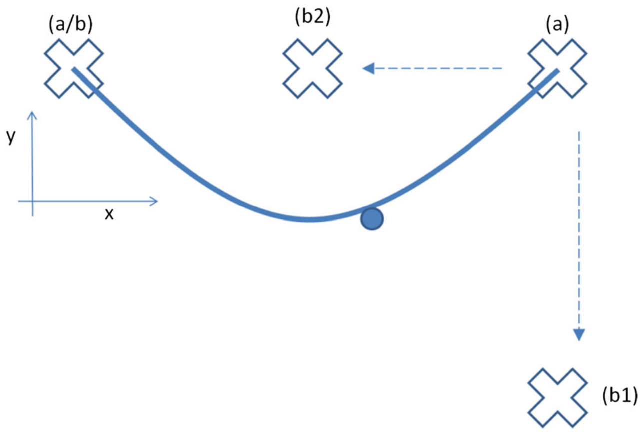


Fig. 7 Example of motion being indicative of keeping or loosing contact

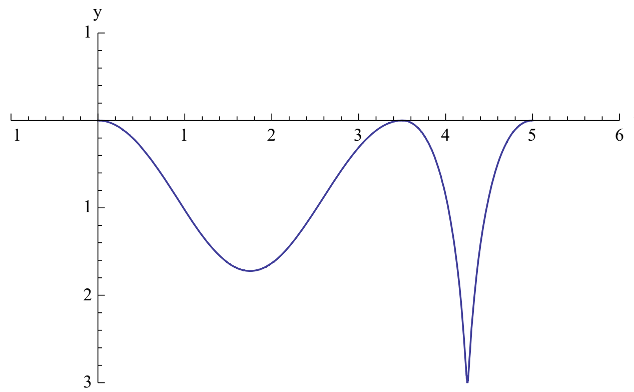


Fig. 10 Intermediate contact point with fixed inclination

3 Fixed points as obstacles: extra conditions and ambiguities

As explained, the addressing of obstacles can be handled by regarding them as extra conditions. Thus, extra variations in curvature changes are permitted. As shown in Fig. 3, two cables, complying with the same equation (i.e., second order differential equation) can have a different shape, depending on whether they have intermediate grasping points or not (continuous vs. dotted line, respectively). The postures are denoted with [a1] and [a2], respectively. Gravity is considered being in the -*y* direction. The length units are also considered being [m] from now on.

Fig. 8 Sudden slowing down may cause contact during oscillation

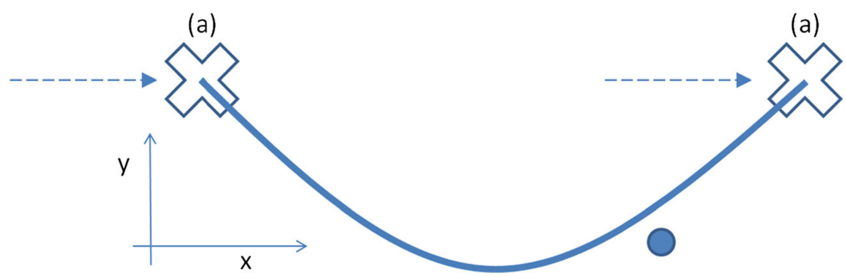
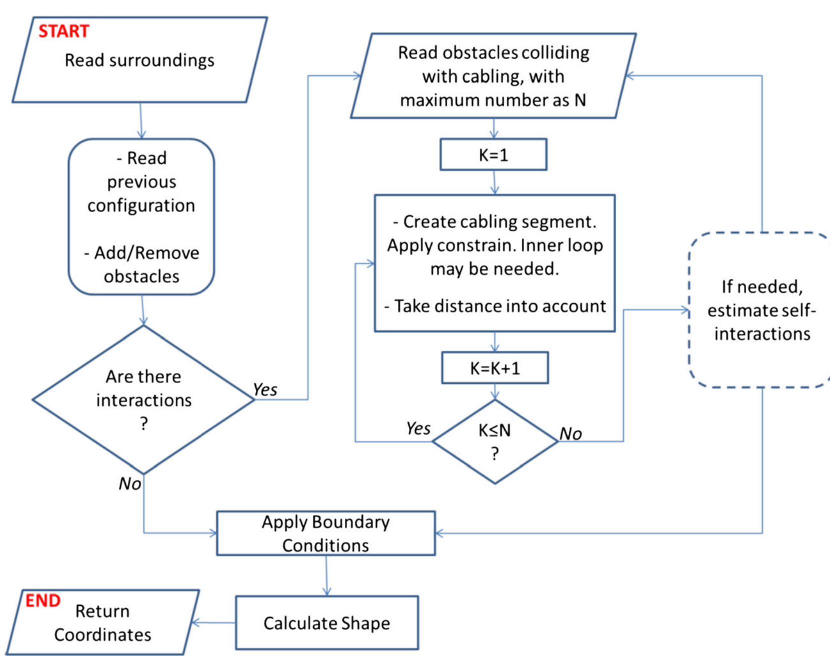


Fig. 9 Flow-chart illustrating algorithm of simulating interaction between cable and surroundings



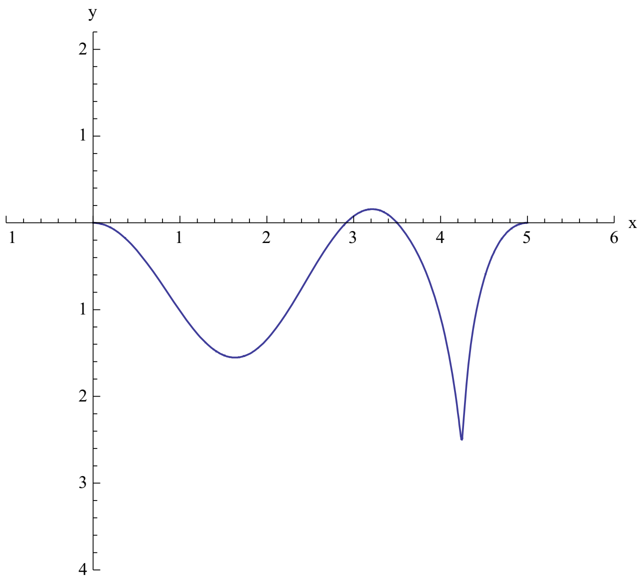


Fig. 11 Intermediate contact point with free to be set inclination

3.1 Friction as constrain

Cases like the one indicated in Fig. 4, where a part of the cable is on the ground and is being drawn, are highly dependent on the contact type between the cable and the ground.

Therefore, a categorization of friction approximation has to be performed. A suggested categorization of the types of contact between two objects can be the following:

- F∞, where the interaction between the bodies is considered being a bond, unless the cable is stretched and accepts a fully tensional force.
- FØ, where no friction is considered.
- FR, where the regularized law [19] is considered.
- Fσ, using the signum function [20], where the friction is opposite to the velocity of steady measure and finally.
- Fd, where a definition function is used to describing the friction.

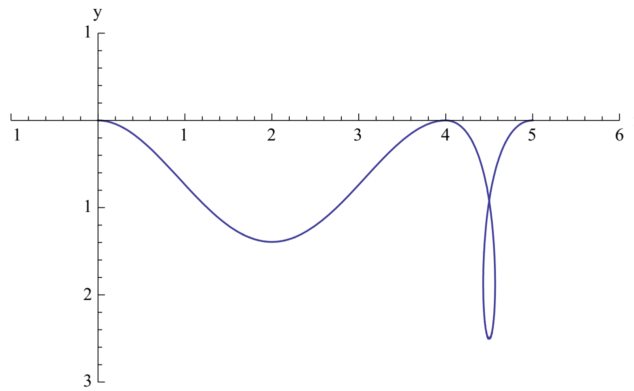


Fig. 13 A transparent cable-cable (self-) interaction, implying twisting in the real world

The first two types seem to be very useful in cases of quasi-static approaches, such as the current one. As explained in Gradient cable, a touch-down experiment can be used to define if the quasi-static approach is appropriate. In Fig. 5, an FØ type obstacle has been regarded and it is denoted by a circle filled with lines (⊛). If it is set in position P, as the grippers lower from case (a) with the resulting cabling shape [a], the cable is split into two parts, configuring the posture [b]. Should the obstacle be moved to position Q, the weight and the tension of the cable will result in the configuration [c]. What is more, the [c] configuration (having a stretched part) is also acceptable for the obstacle's position P, resulting in an ambiguity; however, it is up to the motion history to specify which one of the two cabling shapes is the final one. It is noted here that in the latter sections, the case considered is the F∞, unless stated explicitly otherwise. Ending points on the left for postures [a], [b], and [c] are A, D, and D, respectively. Right ending points are B, C, and C, respectively.

3.2 Distance as criterion

Friction, however, is not the only definitive factor of the cable shape. As shown in Fig. 6, an F∞ case is considered. As the

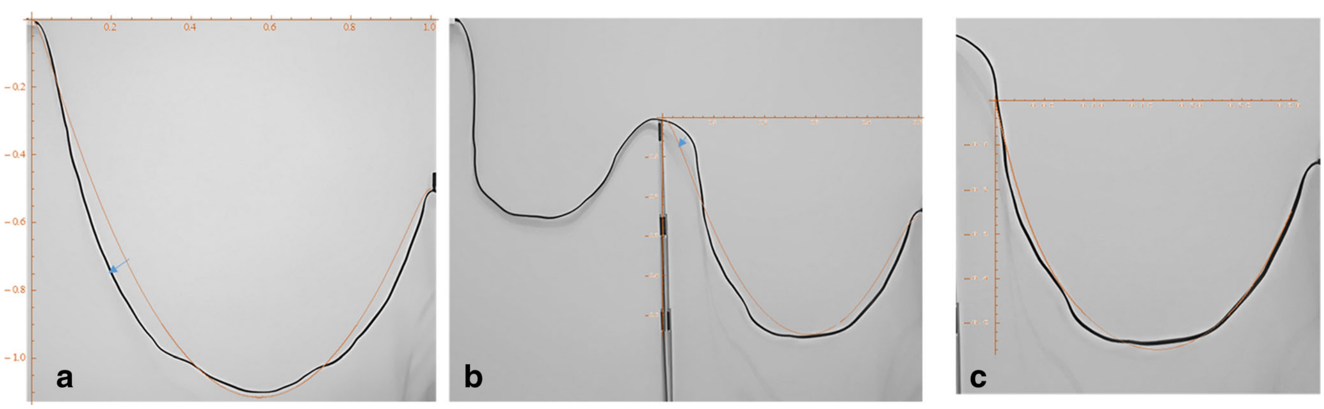


Fig. 12 Intermediate contact point with fixed inclination. Theoretical prediction in orange color. **a** Simple Curve, **b** Curve with obstacle, **c** Details of Curve with Obstacle

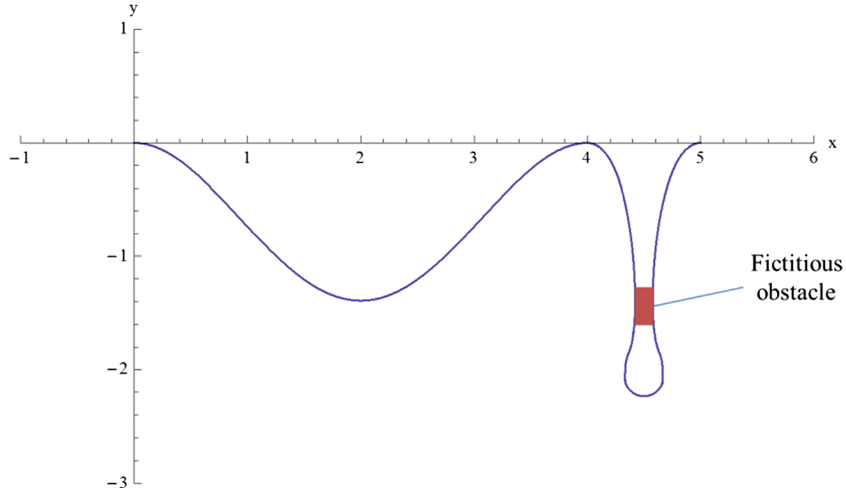


Fig. 14 Fictitious obstacles preventing self-interactions

grippers lower towards the configuration (b), the cable is split into two catenaries. Then, the left gripper keeps moving to the left, until configuration (c) is reached and the [c] cable shape is observed with end point E, resulting in two parts: one straight line and one catenary. If then, the gripper continues moving to the left, since the distance between the gripper and the obstacles exceeds the value of half the physical cable length, both parts of the cable will be stretched out in order to reach configuration [d] with end point F. This is an extreme reachable configuration. If the gripper then moves, this may be catastrophical.

3.3 Motion as condition

In Fig. 7, a cable shaping a catenary is merely touching an obstacle in terms of an F∞ contact. The motion of the right gripper is definitive of the phenomenon's evolution. If it reaches the final position (b1), then a constraint will continue to exist. However, should it move towards the position (b2), there will be a time point that the cable will cease being in contact with the obstacle.

This is not the only case that the existence of a constraint will depend on some kind of motion. In Fig. 8, if the grippers move simultaneously and reach the configuration (a) and stop, in such a way so as for the cable to oscillate, then it is up to the motion profile and the dynamic characteristics of the cable whether or not there will be any sort of interaction between the cable and the obstacle. Such dynamic cases are not a part of the current study.

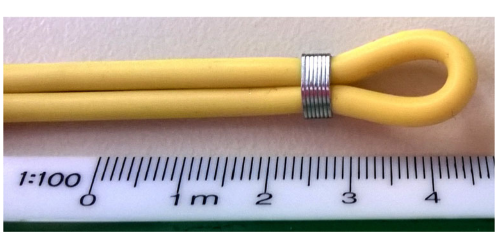


Fig. 15 Real cable photo indicating minimum curvature

4 Algorithmic simulation

The algorithm adopted for the collision handling encapsulates most of the cases presented above (except for dynamics, for simplicity reasons). Under the assumption of pseudo-equilibrium and taking into account the principle of Fig. 2, an algorithm has been implemented. Its abstract description is given in Fig. 9, below.

The main idea advantage of the current algorithm (shown in Fig. 9) is that it skips the ambiguities presented in Fixed points as obstacles: extra conditions and ambiguities with process simulation environment. For every given time step, there is a specific robot-cable combination, leading to a specific posture. This way, it is easy to check established and already installed in Thread 2 collision detection algorithms and be able to estimate how many segments of cables are going to be needed for the next time step.

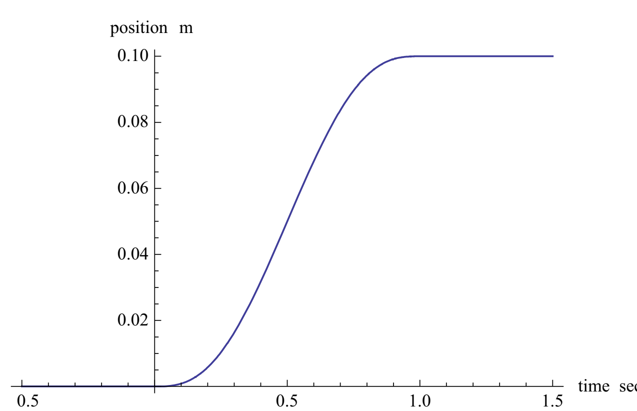


Fig. 16 Smooth motion with polynomial profile in time

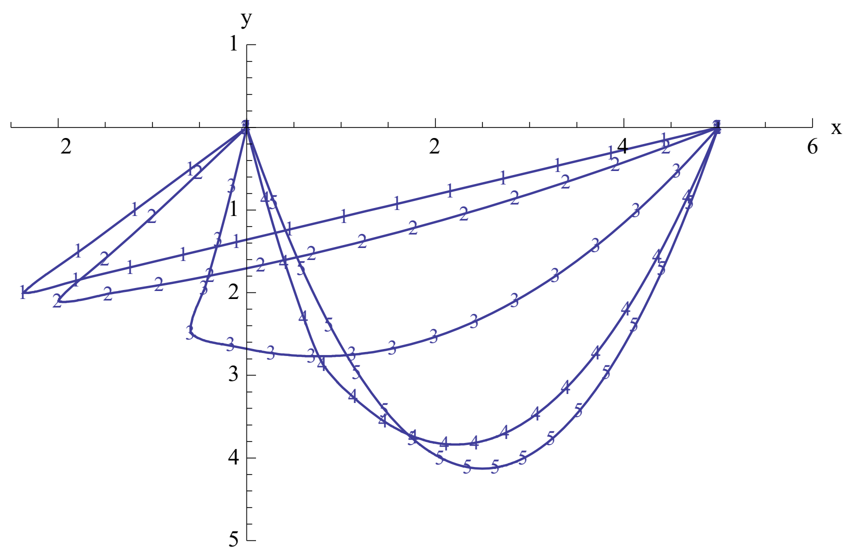


Fig. 17 Artificial motion of a cable losing contact with the obstacle

5 Special topics and experimental verification

5.1 Gradient cable

Moreover, cable-like structures can accept moments [2]. In such a case, the inclination of the cable towards the grasping points is also of a concern. Below, there are two cases of such studies. In the corresponding examples, two grippers are considered being at the two ends ($x = 0$ and $x = 5$), as well as one obstacle ($x = 3.5$). In accordance to the *Fn* definition above, in Friction as constrain, the *Gn* indicates the kind of grasping point regarding the inclination as follows:

- The first case (Fig. 10) could be denoted as G∞, where the inclination of the cable is considered to being pre-assumed and equal to zero degrees
- GØ (Fig. 11) is the second case, where the inclination is considered being free to be chosen from the solution of the mechanical problem

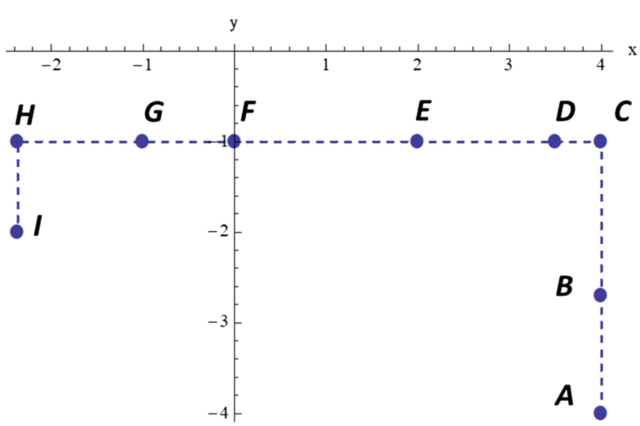


Fig. 18 Motion of the obstacle in space (*x*-*y*) and in time

In the second case, the inclination is a result of minimizing the length of the cable, as shown in [2]. Both cases may be relevant; however, G∞ is considered to be correct with respect to physics when dealing with interactions with other objects, since two boundary conditions are required by the nature of the differential equation. The inclination is dictated by the tangent of the shape of the obstacle. A series of quasi-static “touch-down” experiments can be used to validate in each case study the type of interaction.

Regarding the model efficiency, below, indicatively, a comparison of a cable posture is in real world is given with its model. The model used as per the touch-down experiment in Fig. 12 is F∞G∞. It is an extreme case, as the cable suffers from plastic deformations. Even in this case, however, the (maximum) error is limited within 1.4% for case (a) and 1.2% for case (b). It is proved through case (c) where only the “good” part of the cable has been taken into account, that the plasticity is the main cause of the error.

5.2 Self-interactions

Regarding the self-interactions of the cable, there are numerous cases suggested by the authors:

- Transparent cable-cable interaction, as shown in Fig. 13. This is not a real-world case (especially in 3D; in 2D it could imply twisting).
- F∞ cable-cable interaction, implying contact mechanics geometric approximation.
- Fictitious obstacles approach; adding such additional obstacles could give extra attributes to the cable. Adding one more segment with fixed ends and fixed inclinations is the approach to achieve this.

The last one is depicted in Fig. 14, where artificial constraints have been added to prevent two ends coming close to each other. This approach is very promising towards the description of physical phenomena, since real cables cannot overcome a specific curvature. In order for this to be proven, a real cable was forced to be folded and a binder clip was set up (Fig. 15). A force was then applied to make the cable pass through the binder clip. The cable showed resistance that resulted in a minimum curvature shape, as shown in Fig. 15.

For the repeatability of experiments, it was mentioned that the cable diameter was 0.33 cm compressible by hand until 0.2 cm, while the curvature diameter was measured to be ca. equal to 0.57 cm (transverse diameter).

5.3 Considering dynamics

Furthermore, sudden loss of interaction may lead to free motion. Therefore, here, under the assumption of smooth variations, in the simulation software, the motion can be smoothened via polynomial evolution in time, as shown below, in Fig. 16. The (finite) relaxation time can be estimated either empirically, or through the restoration time of a linearized pendulum with resistance from the air as damping. This polynomial equation (Eq. 1) can be different for every node of the cable and can achieve zero velocity and acceleration at starting and ending time points.

$$r(t) = a_0 + a_1\, t + a_2\, t^2 + a_3\, t^3 + a_4\, t^4 + a_5\, t^5 \qquad (1)$$

Artificial overshoot or oscillation characteristics [21] can be added; however, more details about the dynamics modeling of a cable will be given in a later work. Using 18 points for the cable, the following figure perhaps indicates the motion of a cable going from posture 1 to posture 5 in 1 s (Fig. 17).

6 Case study

The case study comprises of two steps: (i) the numerical verification of the algorithm and (ii) the integration in a simulation commercial software.

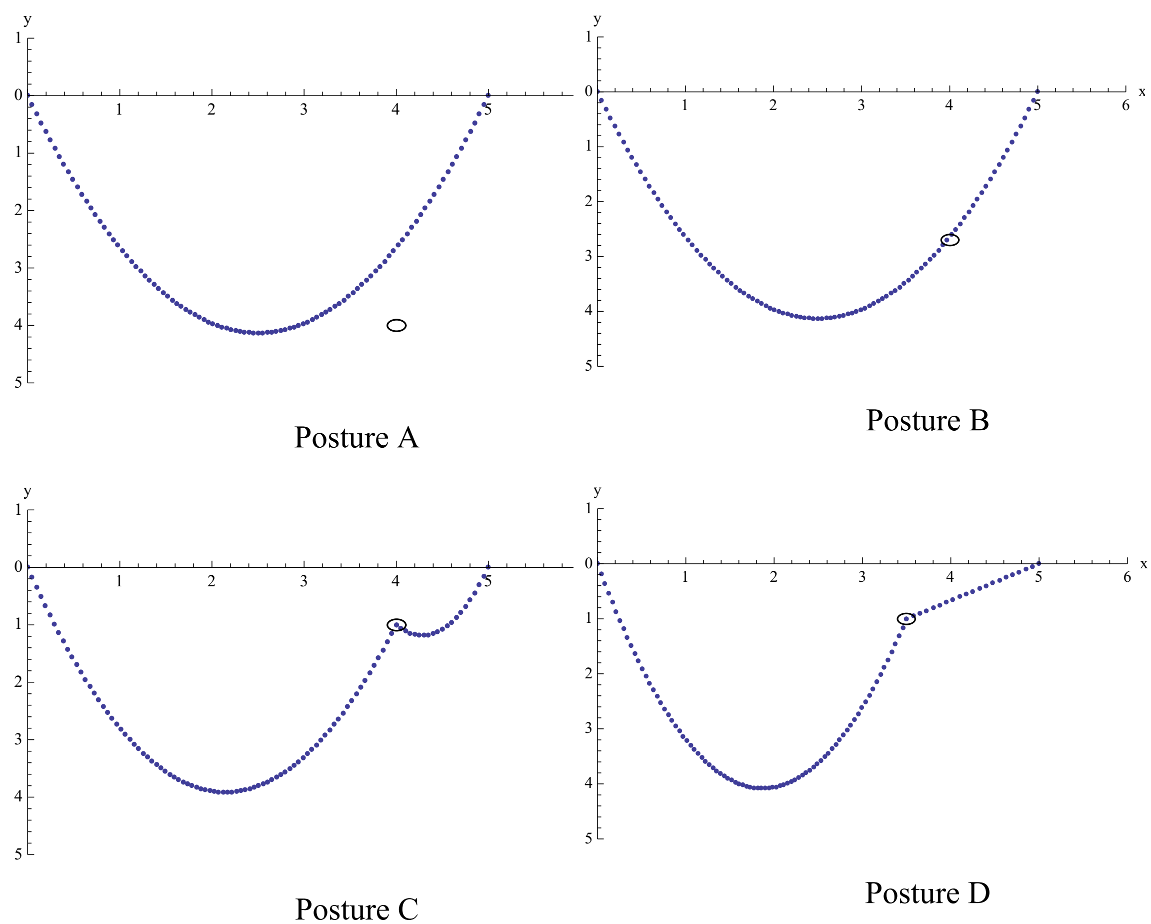


Fig. 19-22 Postures A-D providing the cable shape predictions when the obstacle lies at point of interest

6.1 Case study I

Regarding the first step, a cable equal to 12 length units has been considered to be grasped at both ends ($x = 0$ and $x = 5$). For simplicity reasons, it has been considered being non-moment-accepting. The gravity is in the -y direction. Moreover, a moving obstacle has been considered. Its motion along with the positions of interest is shown in Fig. 18. The following figures provide the cable shape predictions, as postures A–I, when the obstacle lies at these points of interest (Figs. 19, 20, 21, 22, 23, 24, 25, 26, 27).

6.2 Case study II

Regarding the second step of the case study, the following figures show screenshots from the integration of the

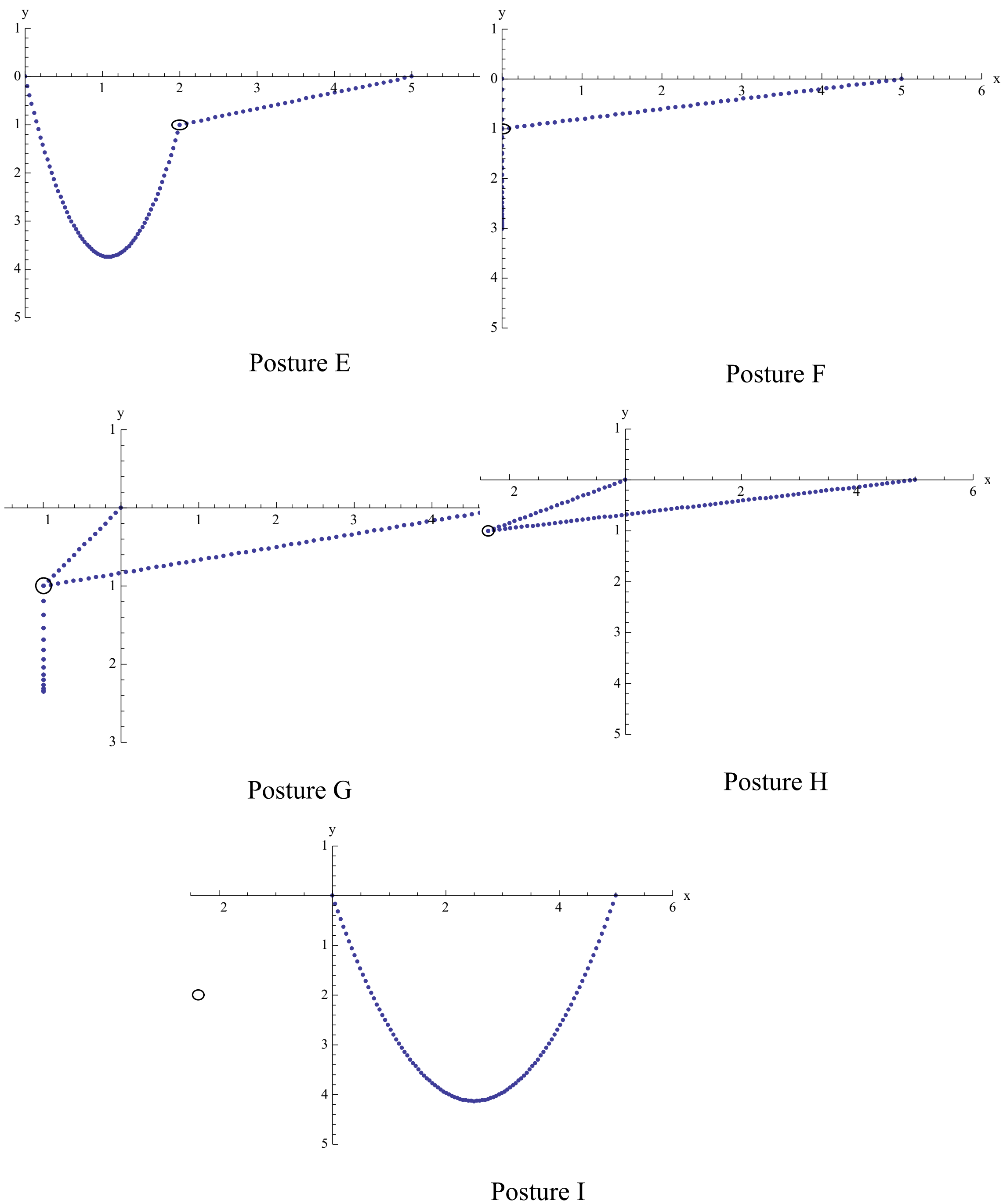


Fig. 23-27 Postures E-I providing the cable shape predictions when the obstacle lies at point of interest

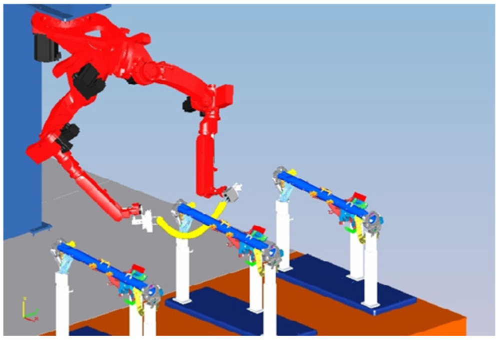


Fig. 28 Screenshot 1 from simulation environment

algorithm in a commercial simulation software. The scenario is the automated assembly of a harness in an automotive pilot case. The left arm first moves vertically (screenshots 1 and 2) and also horizontally (screenshots 3 and 4), towards the viewer (Fig. 28).

As described above, the communication between the shape calculator and the simulation environment is performed successfully with the help of sockets, extending the work described in [2], towards their interaction with the surrounding entities. From the physics point of view, the observation made in screenshots 2 and 3 (Fig. 29—horizontal motion) is the interaction of the cable with a dashboard, in a corresponding automated assembly scenario. The same kind of interaction is shown in Fig. 30, where in screenshots 4 and 5, the motion has been considered to be vertical.

7 Conclusions and outlook

A simulation algorithm, regarding the collision handling between a rigid body and a manipulated cable-like structure, has been implemented. The algorithm overrides the physics by considering a series of geometrical constraints. It has also been proven that it is useful for the cases of the simulation as it can take into account even cases that the cable cannot be modeled in the traditional way.

Consequently, taking into account the assumption of the quasi-static behavior, the algorithm can overcome the cases of the following:

- Friction
- Orientation enforcement
- Self-interactions

In the future, dynamics of the cables will be studied and the algorithm will be enriched to include such cases as well. Regarding the interaction with other bodies, phenomena such as those using the cable for the elevation of other bodies will be integrated. Finally, more complicated phenomena, namely the stick-slip from the dynamics and twisting mechanics, will be introduced into the algorithm.

Funding information The work reported in this paper was partially supported the project X-act/FoF-ICT-314355, funded by the European Commission in the 7th Framework Programme.

Fig. 29 Screenshots 2 and 3 from simulation environment

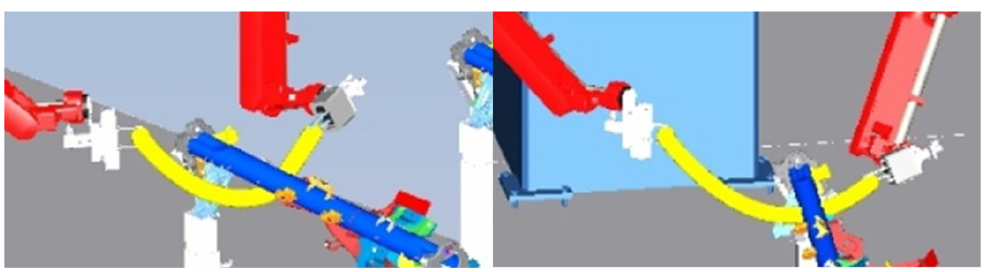
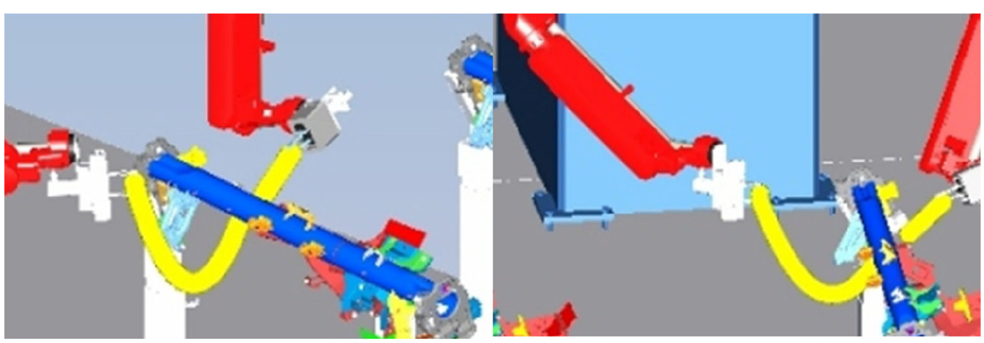


Fig. 30 Screenshots 4 and 5 from simulation environment



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