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ORIGINAL PAPER

Interactive cable harnessing in augmented reality

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Abstract The paper deals with a detailed description of a computer-aided methodology to support the interactive design of cable harnessing. The proposed methodology is implemented using Augmented Reality in order to create and collimate virtual cables directly into a real scene with physical objects. Details about hardware setup and the user interface development are herein discussed. The cables have been modeled with a mathematical formulation involving elastic splines in order to implement their exact physical behavior. The algorithm for the interactive placement and movement is developed using a constrained minimization of potential energy.

Keywords Augmented reality · Cable harnessing · Spline · Elastic spline

1 Introduction

Cable harnessing is a very important activity in the design of electromechanical products. Indeed, all these components need wiring connections among parts, and cable harnesses may have a considerable cost in the development of the entire engineering system.

The main objective of cable harnessing is to determine satisfactory routes for bundles of cables inside a chassis. A route is well-designed when it is a good compromise between different factors: length of cables, free space to be occupied, distance from dangerous components (for example hot or moving parts), possible electromagnetic interferences, accessibility for maintenance, controlled deformation of bends, etc.

The problem of harnessing is solved constraining the routes using specific clips and fasteners that guide the cables. Figure 1 shows an example of a virtual prototype of electrical equipment with principals components.

The design of cable harnesses is often only addressed at the end of the product design process. The related activities are often performed manually with time-consuming and costly tasks. Scientific literature reports an increasing trend in using computer-aided tools to support the design of cable routes [1]. During last decades, many researchers have attempted to develop semi-automate or automate algorithms for the choice of harness path through the use of expert systems in conjunction with CAD systems. Such methodologies are used as a review tool to use after the equipment has been designed [2,3]. Other researchers postulated that harness design is a dynamic process and it is not feasible to automate the entire activity by computers [4]. More recently, some authors proposed to use immersive environment of virtual reality in order to support the virtual process of harness design [5–7].

During last years, many other papers focused on the increasing trend of using augmented reality [8,9] to support a variety of engineering activities, developing interactive tools [10], from geometrical modeling [11], to assembly simulation [12], to analysis [13].

The augmented reality (AR) deals with the combination of real world images and computer generated data. Most AR research is concerned with the use of live video imagery which is digitally processed and *augmented* by the addition of computer generated graphics. The purpose is to extend the visual perception of the world, being supported by additional information and virtual objects. One of the main advantage in the use of augmented reality in engineering is that virtually designed objects can be merged to the real world. For the

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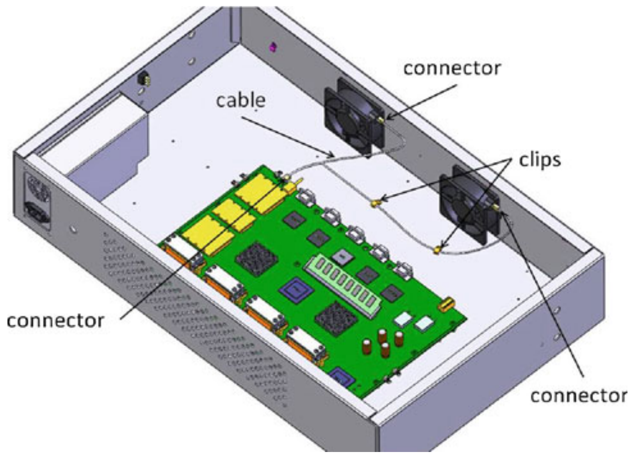

Fig. 1 A virtual prototype of an electrical appliance with components, connectors, cable routes and clips

specific purpose of harnessing design, the user can operate directly into a real product, routing virtual cables which can be superimposed and collimated to the real components. This approach is also useful for improving the training of technicians and testing maintenance procedures.

Another advantage of using augmented reality is the possibility to implement an high level of interaction with the scene. For this reason specific interfaces have to be developed in order to track the position of the user in the scene and interpret his intent.

The paper is organized as follows. In a first section the interactive design of cable harnesses is addressed. Details about objective and specifications are discussed. In the second part, hardware implementation of an augmented reality system are described, focusing on the development of interactive interfaces together with mathematical aspects. In the third part, a mathematical model for the simulation of the physical behavior of the cables is presented using the theory of elastic splines. In the last section an example of application is reported and discussed.

2 Interactive computer-aided design of cables

The harnessing design starts with the following specifications:

- geometry of all components (including the case of the equipment);
- location of the connectors (start and end points of the route);
- safe space for cable path.

The task of the designer is to decide the route of the cable which connects two connectors (see Fig. 1), by placing a set of clips that constrain the cable, avoiding obstacles and excessive deformation.

In modern computer-aided design applications, the cable route is described with a curve in space, due to slenderness and flexibility of the wires. The curve may be mathematically described using B-spline or NURBS [14] which allow to deal with a parametric piecewise expression useful for computation, visualization and building of virtual models. The effects of connectors and clips can be taken into account defining algebraic equations which constrain the curve. The solution of the design problem can be performed automatically (finding a curve and a set of clips that fulfills all the requirements using a numerical routine) or user assisted (interactively and directly by the user). Automatic solutions very often need manual refinement and the user has to change the path of the cable in order to satisfy other heuristic requirements which cannot be described using mathematical equations. According to many researchers [4], the active role of the user is very important to take into account qualitative aspects.

The active role of the designer can be implemented with real-time interaction between the user and the virtual model. This means that the cable route can be real-time updated by the designer that can evaluate whether the solution fulfills the design requirements. With a standard computer-aided design approach the user sketches the curve describing the cable route inside a virtual model of the device. With the use of the augmented reality, the user can observe the cable path from different perspective in a real space, together with real objects. Moreover, he can interact with the cable model in an actual 3D space, which is more natural and intuitive. By this way, it is also easier for the user to understand the spatial relationship between the virtual cable and components and the real device.

In order to ensure not only a visual merging of virtual contents but an active modification of the scene, specific communicators have to be implemented. Their role is bridging real world and virtual objects and their implementation is discussed in the next section. For an accurate and reliable simulation of real-time sketching of the route is very important to take into account the physical behavior of the cable. It means that all the actions on the cable have to be congruent to physics and mechanics of a deformable slender structure. This aspects is important not only for a realistic behavior, but also for obtaining reliable results for successive part dimensioning.

The design algorithm for interactive sketching of a virtual cable can be formulated as follows:

1. The user picks the two connectors of the route. They determine both start and end point of the cable and direction of the tangent vectors.
2. A preliminary cable route can be automatically sketched in order to build a first virtual model of the cable.

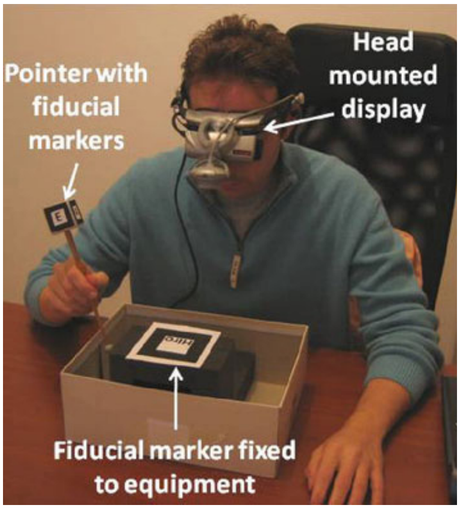

Fig. 2 The augmented reality system which is implemented

3. The user can change the shape of the route by picking and moving (pushing and pulling) points, defining the position of the clips. The cable path has to be updated accordingly. Its modification has to be congruent to physics and mechanics and the type of constraints introduced with clips.
4. The step 3 has to be repeated until the route is satisfactory.
5. The results of the design process is the length and the cable route and the position and the forces acting on the clips.

3 Augmented reality setup and user-scene interaction

The implemented augmented reality system is made of input, processing and output devices (see Fig. 2). Input devices acquire a real world video stream and user's actions. Output devices have to project an augmented perception of the real world enriched with virtual objects. Processing unit has to manage inputs coming from different devices, store and arrange data flows and render the augmented video stream. The hardware is similar to that implemented in a previous work [12].

The input video device is a Microsoft LifeCam VX6000 USB 2.0 camera, able to catch frames up to 30 Hz with a resolution up to 1,024 × 768 pixels. This camera has been rigidly mounted on an Head Mounted Display.

The device to acquire user's intent is a stick pointer on which 5 patterned marker has been rigidly placed onto a cube at one end.

The output device is an Head Mounted Display equipped with OLED displays (Z800 3D visor by Emagin—http://www.3dvisor.com/). It is able to support stereovision up to a resolution of 800x600 pixels each eye.

The processing unit is a personal computer with a Pentium IV quad core processor, 3 Gb RAM, NVidia Quadro FX3700 graphic card, the operative system is Windows XP professional and the development suite for programming is Microsoft Visual Studio 2005.

A patterned marker is also included in the system. It is fixedly placed in the scene (on the equipment to be cabled) and defines the world coordinate system. All the procedures about the recognition of the markers in the scene and the assessment of relative transformations between camera and each marker have been implemented using ARToolkit 2.73 libraries that are widely used to developed augmented reality applications. By means of image processing, involving the detection of marker boundaries and pattern correlation, it is possible to compute the relative transformation between the camera and each visible marker. Further details about ARToolkit and source codes are freely available together with documentation at http://sourceforge.net/projects/artoolkit.

With reference to Fig. 3, the relative transformations between markers and camera that can be computed by image processing are 6:

$[T]_{world}^{camera}$ is the relative transformation between the word reference frame ($O_w - X_w, Y_w, Z_w$) and the camera;
$[T]_{pen,i}^{camera} (i = 1, \ldots, 5)$ are the relative transformation between each marker on the pointer stick and the camera.

The transformation of the tip of the pointer stick with respect to the world reference frame $[T]_{tip}^{world}$ can be evaluated using:

$$[T]_{tip}^{world} = \left([T]_{world}^{camera}\right)^{-1} \cdot [T]_{pen,i}^{camera} \cdot [T]_{tip}^{pen,i} \tag{1}$$

The (1) can be evaluated using the transformation of any of marker placed on the pointer stick. In order to improved the precision and stability of the evaluation, it is a good practice to use the marker whose z axis forms the smallest angle with the normal direction to the camera image plane. Indeed, this marker appears less distorted and the image analysis can be performed more accurately.

The (1) relates the position and attitude of the pointer stick to that of the world reference frame. Since the marker defining this coordinate system is attached to the equipment to be cabled, the (1) controls the position of the pointer stick with respect to the equipment itself.

4 Considering cables as splines: theory of elastic spline

Consider a cable with a cross section S. The neutral fiber or neutral axis is the oriented curve of length L that passes through the center of every cross-section. The neutral fiber

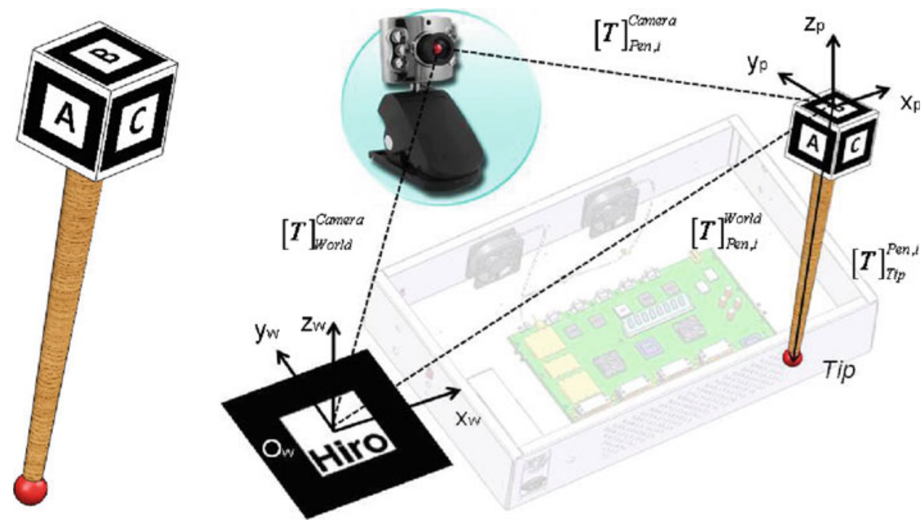

Fig. 3 The pointer stick with patterned markers (on the *left*) and the mathematical transformation among camera, world and pointer reference frames (on the *right*)

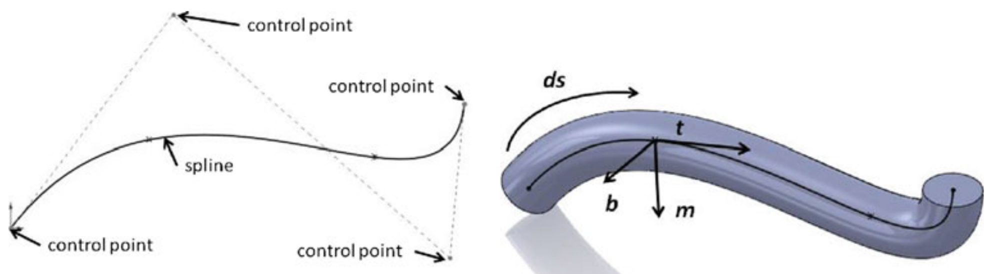

Fig. 4 An example of spline modeling (on the *left*) and the Frenet moving frame of the curve (on the *right*)

can be geometrically expressed with a spline as shown in Fig. 4. A spline is a piecewise polynomial expression of a curve in parametric form [14]. Considering a set of m control points $\{\mathbf{P}_0 \ldots \mathbf{P}_{m-1}\}$, a spline can be expressed by means of the general formula:

$$p(u) = \sum_{i=0}^{m-1} b_i(u)\mathbf{P}_i \tag{2}$$

where $b_i(u)$ are the blending functions (polynomial functions of the variable u) fitting the control points. In general, the blending functions depend on the degree of the polynomials, the numbers of control points and the knots sequence [14]. The control points can be considered the degrees of freedom of the spline. Except for the first and the last control point, the curve doesn't pass through them, but their position in space influences the shape of the spline (Fig. 4, on the left). These variables do not have a direct physical meaning (as the nodes in the finite element approach), but are mere mathematical entities.

In order to relate mathematical to physical properties of the spline we have to introduce mechanical elasticity of the spline, combining physics-based constraining equations with spline geometry [15,16]. This approach allows to manage the simulation of a complex and large displacement of a 1D element (as the cable) in terms of a polynomial closed form expression, deducing geometrically exact expression involving elastic energy [17,18].

According to (2), the shape and attitude of a spline is regulated by the location of its control points. For this reason they are considered the degrees-of-freedom of the curve (i.e. of the neutral fiber of the cable). When the control points are displaced, the spline moves and changes its shape accordingly.

For a 3D curve with m control points we have $3 \cdot m$ degrees of freedom (3 translations of each point) $\{q_1, \ldots, q_{3m}\}$. For this reason, the ith control point can be expressed using a 3-parameter vector:

$$\mathbf{P}_i = \{q_{3i-2} \quad q_{3i-1} \quad q_{3i}\}^T = \{x_i \quad y_i \quad z_i\}^T \tag{3}$$

The elastic energy of a 3D cable considered as a spline is composed of three terms and can be written as:

$$U_{cable} = U_{bending} + U_{stretching} + U_{twisting} \tag{4}$$

where:

U_{cable} is the elastic energy of the cable deformation;
$U_{bending}$ is the term of elastic energy of the cable due to bending;

$U_{stretching}$ is the term of elastic energy of the cable due to stretching;
$U_{twisting}$ is the term of elastic energy of the cable due to geometrical twisting;

Before discussing the details about the computation of the (4), it is useful to review some key geometrical concepts about splines. In particular, in order to simplify the computation of local geometrical properties of a curve (e.g. tangent vector, curvature, etc.) it is useful to introduce the Frenet frame, which is a local frame moving along the curve (Fig. 4, on the right). Assuming that the curve is given in the algebraic form (2), the unit vector associated with the Frenet coordinate system can be expressed as follows:

$$t(u) = \frac{p'(u)}{\|p'(u)\|} \quad \text{is the tangent vector} \tag{5}$$

$$m(u) = b(u) \wedge t(u) \quad \text{is the normal vector} \tag{6}$$

$$b(u) = \frac{p'(u) \wedge p''(u)}{\|p'(u) \wedge p''(u)\|} \quad \text{is the binormal vector} \tag{7}$$

where:

$$p'(u) = \frac{\partial p(u)}{\partial u} \text{ and } p''(u) = \frac{\partial^2 p(u)}{\partial u^2}$$

Considering the changing of the Frenet frame along the curve it is possible to define two scalar parameters: the Frenet curvature $\kappa(u)$ and the Frenet torsion $\tau(u)$:

$$\kappa(u) = \frac{\left\| p'(u) \wedge p''(u) \right\|}{\|p'(u)\|^3} \tag{8}$$

$$\tau(u) = \frac{\left(p'(u) \times p''(u)\right) \cdot p'''(u)}{\|p'(u) \times p''(u)\|^2} \tag{9}$$

These entities which are independent from the parameterization [14], will be used to evaluate the deformation of the spline.

Let us now discuss in details the computation of the three terms in (4). The bending elastic energy is proportional to the square of the variation of the bending strain:

$$U_{bending} = \frac{1}{2} \int_0^L EI \left(\varepsilon_b - \varepsilon_b^0\right)^2 ds \tag{10}$$

where:

ε_b^0 is the bending strain of the free form spline;
ε_b is the bending strain of the deformed spline;
E is the Young Modulus of the material;
I is the momentum of Inertia of the cross section with respect to the bending axis (section of a cable can be considered circular).

The bending strain is expressed with the scalar Frenet curvature $\kappa(u)$:

$$\varepsilon_b(u) = \kappa(u) \tag{11}$$

The stretching elastic energy is proportional to the square of the variation of the stretching strain:

$$U_{stretching} = \frac{1}{2} \int_0^L EA \left(\varepsilon_s(u) - \varepsilon_s^0(u)\right)^2 ds \tag{12}$$

where:

A is the area of the cross section of the cable;
ε_s^0 is the stretching strain of the free form spline;
ε_s is the stretching strain of the deformed spline;

The stretching strain can be evaluated as:

$$\varepsilon_s(u) = 1 - \left\| \frac{dp(u)}{du} \right\| \tag{13}$$

The twisting energy has to be computed taking into account the geometrical torsion τ of the spline, computed using the (9). The twisting strain ε_t can be computed as:

$$\varepsilon_t(u) = \tau(u) \tag{14}$$

Since geometric torsion is not defined for a straight line, we can assume it is zero in this case.

The twisting energy can be written as:

$$U_{twisting} = \frac{1}{2} \int_0^L GI_0 \left(\varepsilon_t(u) - \varepsilon_t^0(u)\right)^2 ds \tag{15}$$

where:

G is the shear modulus of the cross section of the cable;
ε_t^0 is the twisting strain of the free form spline;
ε_t is the twisting strain of the deformed spline.

Consider to place a clip to the cable in a point $\{p(u^*)\}$ of the spline (Fig. 5). If the clip is placed with its axis coincident to the tangent vector of the cable the corresponding spline will be not deformed.

Imagine now to move this clip away to a position close to the initial one. Of course, the cable (and so the spline) will change its shape (i.e. modifying the position of control points) reaching a configuration that minimizes the elastic energy, under the action of external forces exerted by the clip.

In this case, the clip is a constraint for the spline configuration, thus the problem can be addressed with a classical mathematical approach of constrained function optimization.

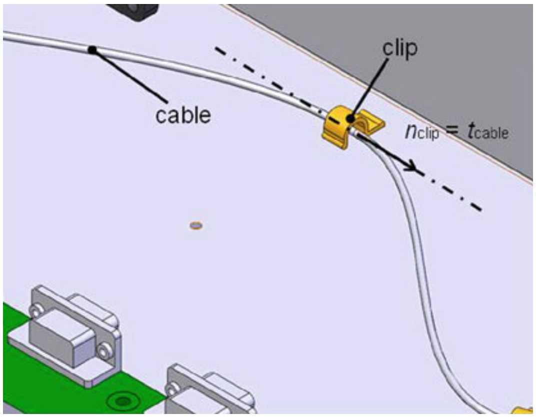

Fig. 5 Placement of a clip which constrains the cable route

The function to be minimized it the overall elastic energy. The constraints to be taken into account are the boundary conditions (ending connection) and the presence of the clip. Let us discuss these constraints in details.

The first set of constraints concerns the movement of the clip. Since the cable has to pass inside the clip, its reference point $\{P_{clip\_new}\}$ will also be a point of the spline:

$$\{\psi_{pos}\} = \{p(u^{**})\} - \{P_{clip\_new}\} = 0 \tag{16}$$

Actually, since the clip does not constrain the spline in its tangent direction, the point on the spline that satisfies the (16) will have a parameter u^{**} different from the starting one u^{*}. Considering that we are taking into account a small displacement of the clip, we can make the following approximation:

$$u^{**} \cong u^{*} \tag{17}$$

This assumption simplifies the (16) into:

$$\{\psi_{pos}\} = \{p(u^{*})\} - \{P_{clip\_new}\} = 0 \tag{18}$$

The (18) is a vector of 3 scalar constraint equations.

The presence of the clip constraints also the normal and binormal components of the spline Frenet frame. In particular they are constrained to be perpendicular to the axis vector n of the clip (Fig. 5). Considering the same approximation in (17), we can write:

$$\{\psi_t\} = \begin{cases} \{b(u^{*})\} . \{n_{clip}\} = 0 \\ \{m(u^{*})\} . \{n_{clip}\} = 0 \end{cases} \tag{19}$$

The (19) is a vector of 2 scalar constraint equations.

The connections at the two ending of the cable, can be also considered as constraints. The presence of a connector can be modeled with two constraining contributions. The first is that the end of the spline has to be coincident to the connector reference point $\{P_{connector}\}$. The second one implies that the tangent vector at the end of the spline has to be coincident to the normal vector to the connector $\{n_{connector}\}$. Considering the *connector0* acting at the start of the cable ($u = 0$) and the *connector1* acting at the end of the cable ($u = u_{\max}$), these constraints can be written as:

$$\{\psi_{c0}\} = \begin{cases} \{p(0)\} - \{P_{connector0}\} = 0 \\ \{b(0)\} . \{n_{connector0}\} = 0 \\ \{m(0)\} . \{n_{connector0}\} = 0 \end{cases} \tag{20}$$

$$\{\psi_{c1}\} = \begin{cases} \{p(u_{\max})\} - \{P_{connector1}\} = 0 \\ \{b(u_{\max})\} . \{n_{connector1}\} = 0 \\ \{m(u_{\max})\} . \{n_{connector1}\} = 0 \end{cases} \tag{21}$$

The (20) and (21) are vectors of 5 scalar constraint equations each.

Collecting all the constraint equations in a single vector $\{\psi\}$, we can write:

$$\{\psi\} = \{\psi_{pos} \quad \psi_t \quad \psi_{c0} \quad \psi_{c1}\} \tag{22}$$

The optimization problem can be mathematically written as:

$$\begin{cases} \frac{\partial U_{cable}}{\partial q_i} + [\Psi]_q^t \{\lambda\} = 0 \\ \{\psi\} = 0 \end{cases} \tag{23}$$

where $[\Psi]_q$ is the Jacobian of the vector of constraint equations with respect to the control points coordinates and $\{\lambda\}$ the vector of the associated Lagrange multipliers. The (23) is a system of 3m+15 scalar equations in 3m+15 unknown and it can be solved to find the m control points coordinates $\{q\}$ and the Lagrange multipliers $\{\lambda\}$.

The system in (23) has been deduced under the assumption of a small displacement imposed to the clip which fulfills the (17). The solution of the optimization is the new position of all the m control points defining the spline. Actually, this modification in shape introduce a small variation δ of length of the cable that can be assessed using:

$$\delta = \int_0^{u_{\max}} \left(\varepsilon_s - \varepsilon_s^0\right) du \tag{24}$$

Since the presence of the clip does not introduce a discontinuity of the stretching force, the stretching strain is constant through all the spline. It means that we can re-parameterize the spline with a new parameter u' proportional to the previous one:

$$u' = \frac{L_0 + \delta}{L_0} u \tag{25}$$

Physically, this voids the stretching strain and represents the use of a new cable length $L_0 + \delta$.

Finally the algorithm can be arranged as follows:

Before the placement of the clip, each frame acquisition:

1. Compute the position of the pointer tip in space;
2. Compute the distance of the pointer tip from the spline;

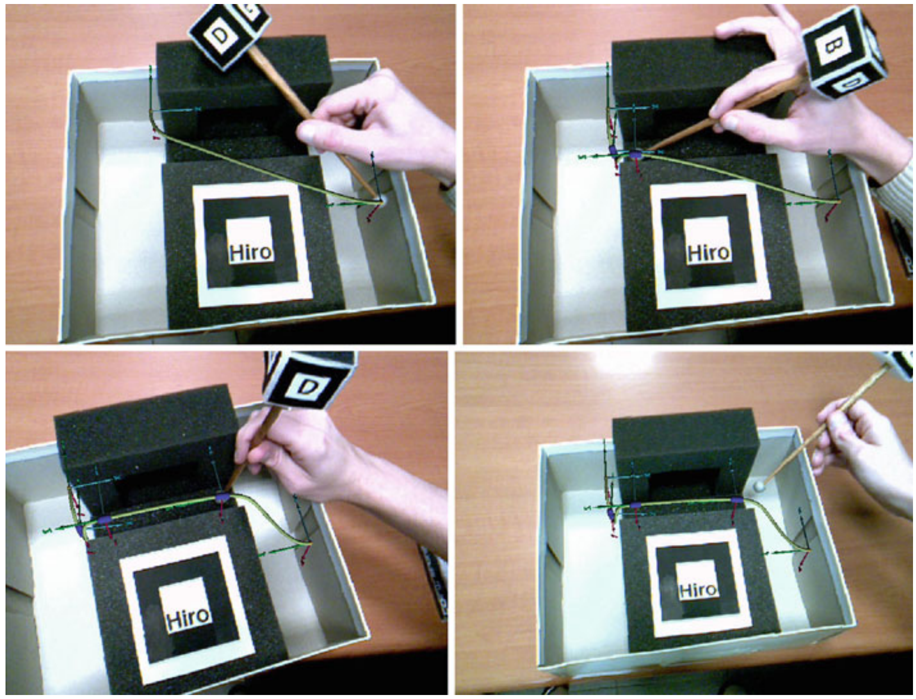

Fig. 6 Snapshots of interactive harnessing using augmented reality (from the user's point of view)

3. If the distance is less than a tolerance, prompt user for picking points and inserting a clip;
4. If the user agrees to insert a clip, record the value of the parameter of the spline at the picking point.

During the placement of the clip, each frame acquisition:

1. Compute the new position of the pointer tip (and so the new position of the spline point);
2. Compute the clip normal vector defined by the pointer tip rotation;
3. Solve the optimization problem using the (23);
4. Compute the stretching strain and the new length of the cable using the (24);
5. Re-parameterize the curve using the (25) and update the value of the parameter in correspondence of the clip.

The algorithm can be repeated for every clip that has to be inserted. In that case new constraint equations as in (18) and (19) have to be appended to $\{\psi\}$ vector.

The solution of the optimization problem in (23) allows to compute also the reaction forces exerted by the clip. The Lagrange multipliers associated to the constraint equations in (18)–(21) represent the forces and torques that clips and connectors have to exert on the cable in order to produce its deformation. The knowledge of these actions is important for the structural dimensioning of clips and fixtures.

5 An implementation example

In order to discuss the aspects of implementation and application, it is useful to introduce an example. It deals with the harnessing of a cable between two connectors inside a box.

With reference to Figs. 2 and 6, the experimental setup includes a marker fixed to the box which defines the world reference frame. Figure 6 reports four snapshots of the implemented example. The point of view is that of the user.

The first action is defining the position inside the box of the two connectors (Fig. 6, top left). As discussed in the previous section, the connectors define the location and the direction of the tangent vector of the start and end point of the cable. Thus the user has to pick 4 points inside the box: two defining the locations and two the direction vectors. If the user confirms the selection of the 4 points, a cable can be modeled. Practice shows that a good compromise between mathematical complexity and the flexibility degrees of freedom is to model a C^2 cubic spline with 10 control points with a uniformly spaced knots. The choice of a cubic spline allows to evaluate the elastic energy accurately. The location of the control points can be found solving the (23) subjected only to the constraints coming from the two connectors [Eqs. (20), (21)].

The next step is defining the location and the attitude of the clips (Fig. 6, top right). For this target the user picks a point on the spline and moves this point inside the box in order to find a convenient location for the clip. During this motion, the cable geometry is updated according to (23), considering the constraints in (18)–(21). After the clip is placed

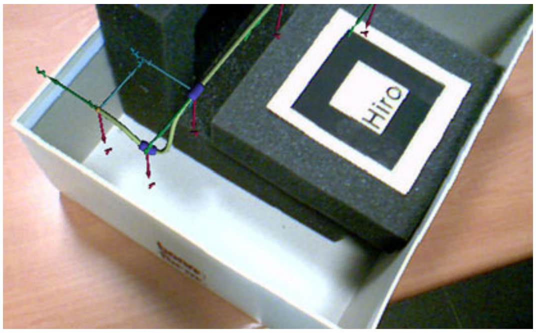

Fig. 7 Detailed view of a portion of the virtual cable with two clips

the user can modify its attitude selecting a point to define a new direction vector. Again, the cable is updated according to (23), considering the constraints in (18)–(21). This step has to be repeated for each clip (Fig. 6, bottom left). Every new clip placement, six constraint equations [like those in (18) and (19)] have to be appended to vector $\{\psi\}$ (23).

The harnessing continues until the cable route can be considered satisfactory and all the black obstacles avoided (Fig. 6, bottom right). During the interactive design, many virtual objects appear in the scene. In addition to the virtual cable, clips may be rendered using different color, geometry and a reference frame (see Fig. 7).

At the end of the interactive harnessing the design outputs are:

- length of the cable;
- location and attitude of the clips;
- forces and torques acting on the clips;
- cable route (described from the location of spline control points).

6 Conclusion

In this paper a methodology for the interactive design of cable routing has been presents. It has been developed using augmented reality in order to allow a real-time sketching and modification of a virtual cable path inside a physical device. The interaction between the user and the augmented scene has been implemented with a special stick pointer whose position in the scene can be optically tracked by pattern recognition. The physical behavior of the cables has been taken into account developing a numerical algorithm based on the minimization of elastic energy of slender structures using the theory of flexible splines. With this implementation, the user can interactively change the path of the cable respecting its physical and mechanical properties, obtaining a reliable and realistic simulation.

The use of the augmented reality for cable harnessing has shown many important advantages. First, the user is supported for designing cable route directly on a physical device, using virtual entities (cables) superimposed and collimated to a real world, giving an illusion of a unique environment. The design of cables can be performed interactively in order to take into account also qualitative and heuristic requirements that a fully automated procedure cannot ensure. Secondly, the use of an optimization algorithm in order to update the path of the cable is compatible to real time processing and rendering of the scene. It means that the refresh of the streaming video is not affected by other computations. This important feature is possible thanks to the description of the cable with a B-spline which allows to an accurate expression of elastic energy and deformation using few mathematical parameters. Moreover, the modelling of cable using B-spline is useful to export, at the end of the design process, the solution into a standard CAD application for further development and for the preparation of technical documentation.

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