Tangible user interfaces for physically-based deformation: design principles and first prototype

Nawel Takouachet · Nadine Couture · Patrick Reuter · Pierre Joyot · Guillaume Rivière · Nicolas Verdon

Abstract We present design principles for conceiving tangible user interfaces for the interactive physically-based deformation of 3D models. Based on these design principles, we developed a first prototype using a passive tangible user interface that embodies the 3D model. By associating an arbitrary reference material with the user interface, we convert the displacements of the user interface into forces required by physically-based deformation models. These forces are then applied to the 3D model made out of any material via a physical deformation model. In this way, we compensate for the absence of direct haptic feedback, which allows us to use a force-driven physically-based deformation model. A user study on simple deformations of various metal beams shows that our prototype is usable for deformation with the user interface embodying the virtual beam. Our first results validate our design principles, plus they have a high educational value for mechanical engineering lectures.

Keywords Tangible interface · Two-handed interaction · Physically-based deformation · ShapeTape

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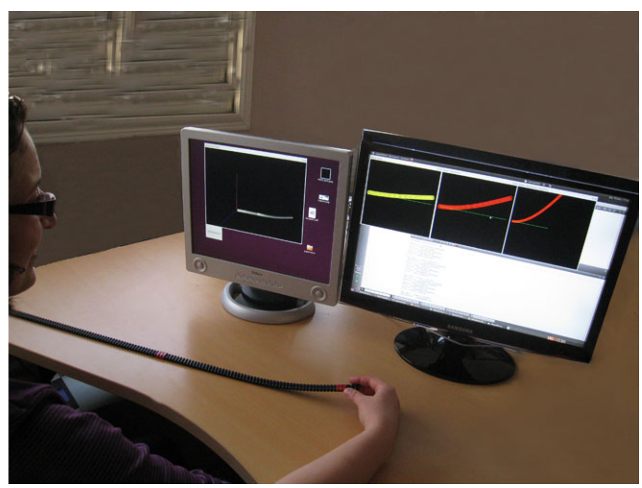
1 Introduction



It is crucial to take into account physically-realistic behavior when deforming 3D models in many fields of application, such as industrial mechanical design, or pedagogical field for understanding mechanical phenomena, or even in archeology in order to understand the chronology of the different deformations that were suffered by archaeological findings.

With recent progress in physical deformation models and increasing computing power, realistic simulations can now be driven at interactive rates. It is therefore relatively natural to aim at improving the usability and efficiency of user interfaces for interactive physically-realistic deformation. We propose using tangible user interfaces because they have proven to be useful for handling 3D models, such as when selecting, navigating and performing deformation tasks. As far as we know, there is yet no passive tangible user interface for deforming 3D models realistically based on an underlying physical model.

As a first contribution of this paper, we present design principles for conceiving tangible user interfaces for physically-realistic and interactive deformation of 3D models. These design principles are the result of ideas by researchers from three different communities: human–computer interaction, geometric modeling and physically-based simulation.

Our design principles, integrating a physically-based deformation method, a 3D model and an input device, highlight the three main issues with regard to the design of such a tangible user interface: (1) How is the 3D model mapped to the input device so that the device embodies the 3D model? (2) How is the information provided by the input device linked to the input parameters of the physical deformation model? (3) How are the output parameters of the physical model used to apply the deformation to the 3D model? Our interaction metaphor is independent of the physical model. However, for interactive deformations the model should allow these to be calculated in real time.

As a second contribution of this paper, we present a first prototype based on these design principles, thus providing a concrete example of how to address these three issues. In our prototype we use the ShapeTape,[1] a passive tangible user interface that literally embodies a 3D beam-shaped model. By associating a reference material to the user interface and by converting the displacements of this user interface into forces, we can still perform a force-driven physically-based deformation model despite the fact that it is impossible to directly capture the applied forces on passive interaction devices. Our first results on simple deformations of a metal beam validate our prototype and the involved design principles. We believe that our prototype provides a high educational value for mechanical engineering lectures.

This paper is structured as follows. In Sect. 2 we briefly present previous work about user interfaces for deforming 3D models. In Sect. 3 we introduce the principles for designing a tangible user interface for driving physically-realistic deformations of 3D models. In Sect. 4 we show a first prototype based on our design principles. In Sect. 5 we present and analyze the user study that we conducted to evaluate our prototype. In Sect. 6 we discuss our results before concluding in Sect. 7 with some directions for the future work.

[1] www.measurand.com.

2 Previous work

Most existing 2D and 3D deformation systems are based on the WIMP paradigm [2, 3, 6, 7, 12, 20]. In order to perform deformations, the user must express successive actions using the mouse, often in combination with various different keyboard shortcuts. In order to go beyond this limitation, much recent work in the research community has concerned the design of new input devices with appropriate interaction techniques that provide an easier and more intuitive user–computer dialog. We especially refer to tangible user interfaces (TUIs) [8] as an emerging and promising approach which is currently being explored. The main idea of tangible user interfaces is to allow the user to control digital information via the intuitive manipulation of objects in the physical world. According to Ullmer and Ishii's definition [17], tangible interfaces give physical form to digital information, employing physical artifacts both as representations and controls for computational media.

Below we briefly overview some of the user interfaces for the deformation task which we classify according to their ability to take into account physically-realistic deformation behavior. First, we shall consider previous work that does not consider a physical model.

Balakrishnan and Hinckley [1] used a tangible user interface for creating and editing curves and surfaces by manipulating a high degree-of-freedom ribbon called ShapeTape. Their application is limited to handling only the geometry of curves and surfaces regardless of the underlying physics. Llamas et al. [11] proposed a system of two-handed manipulation using two magnetic sensors to deform parts of tubular 3D models geometrically. Lee et al. proposed iSphere [10], a bi-manual isometric interface for 3D geometrical deformation. The input interface is a hand-held dodecahedron consisting of 12 capacitive sensors that are used to control a 3D model. Here too the achieved deformation is purely geometric and does not consider the physics of the objects. In addition, the system is limited to handling round shapes.

Recently, Sugiura et al. [16] developed a system which allows both the touch position and surface displacement of soft objects to be detected using a directional photoreflectivity sensor, called FuwaFuwa. This small sensor can be easily installed and integrated in any familiar soft object. We think that this system is promising with a view to designing tangible user interfaces devoted to shape deformation.

Let us now present some of the approaches that take into account physical deformation simulations. Note that these simulations have become feasible at interactive rates due to the ever increasing computational power, especially due to massive parallel processing and by shifting some expensive calculations to a preprocessing step [7, 12, 19]. Blanding et al. [4] have developed ECAD, a Phantom-based haptic system combined with a real-time solver to calculate physically-based deformations. The user of this immersive ECAD system interacts with the virtual model through various input devices, such as the Phantom and a 3D mouse. Even in the nonlinear case of large deformations, the system maintains responses at haptic rates for moderately complex models.

Peterlik et al. [13] used the Phantom as an active and haptic user interface for real-time physically-based deformation. To provide interactive reactions to acting forces, the system applies interpolations of precomputed data. Although the system is quite impressive, problems in terms of associating the force vector with the model still persist because the Phantom does not directly embody the model to be deformed.

Prados et al. [14] proposed an interactive technique to perform elastic deformations of volumetric images reconstructed from two-dimensional computed tomography scan information. To give a natural tactile feeling, the authors applied a wrapping free-form deformation structure adding realistic and physically plausible haptic feedback.

These three methods are the closest to our approach in the sense that they aim to propose interactive techniques to perform physically-realistic deformations. Our point of view is to incarnate the virtual model and to give the users the feeling that they literally take the model in their hands, thus allowing spontaneous interactive manipulation through natural two-handed gestures: we aim to design a tangible user interface. Inspired by the work of Balakrishnan and Hinckley [1], we attempt to exploit the affordance of the ShapeTape, but in addition to their work, we aim to find a physically-based deformation of beam-shaped objects in real time.

3 Design principles

Before presenting our concrete prototype, we present the principles for designing a tangible user interface for physically-based deformation that take into account constraints from the areas of human–computer interaction, geometric modeling and physically-based simulations.

Note that our design principles address the development of tangible user interfaces that fully embody the entire 3D model. Of course, we could have also made the tangible user interface embody only a subpart of the 3D model. However, we would have lost affordance, and thus the users' feeling of having the entire 3D model in their hands. Moreover, successive association steps between the user interface and the subpart of the 3D model would have been required that slightly break the immersive character of the deformation.

The design principles are depicted in Fig. 1. There are three main components: *the 3D model*, *the input device* and

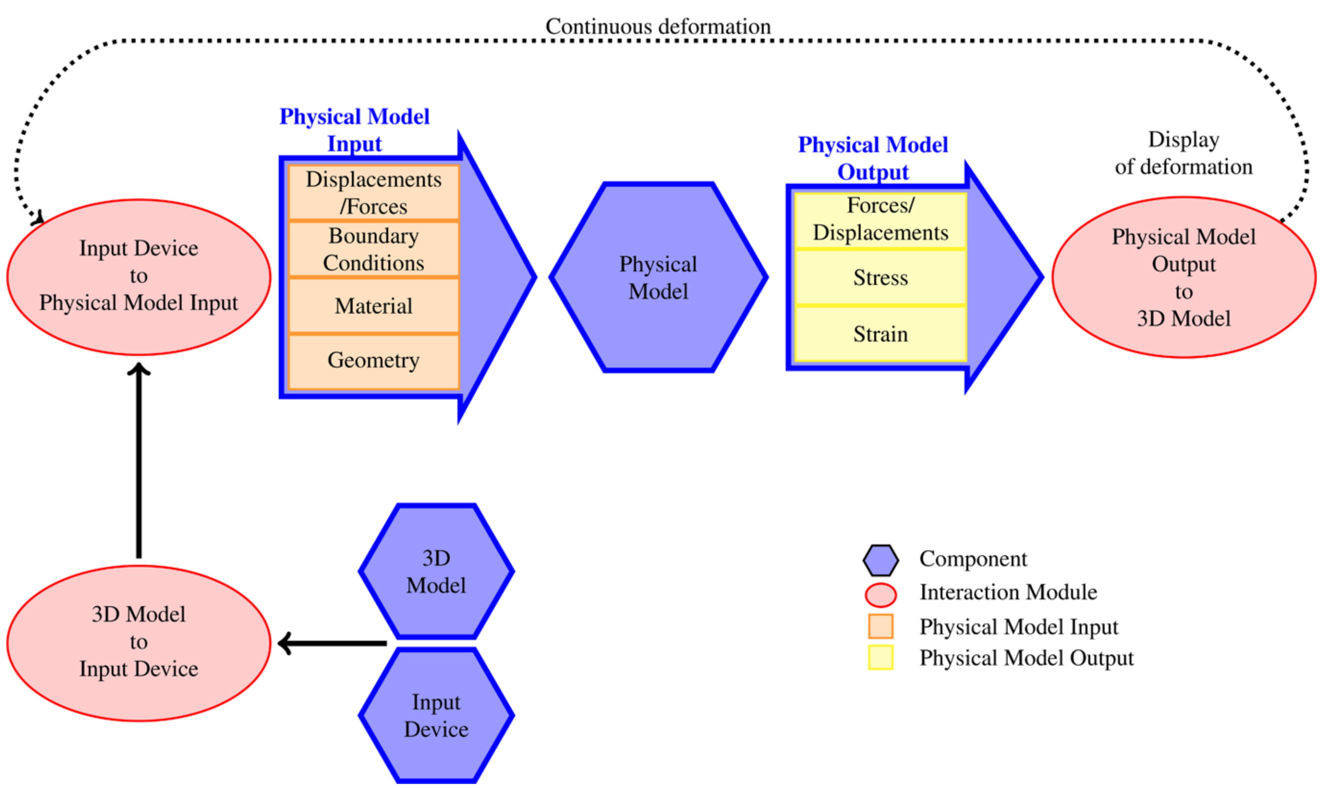


Fig. 1 An illustration of the design principles for a tangible user interface dedicated to physically-realistic deformation

the physical model. The major difficulty is to link these three main components together in order to provide a spontaneous and optimized interaction. Hence, we integrate the three following intermediate interaction modules.

3D model to input device In this first module, the 3D model has to be matched with the input device in order to ensure the tangible embodiment of the digital 3D model. This matching is not trivial, because the shape of the input device may differ more or less from the shape of the 3D model. For example, when we consider the input device as a set of discrete 3D locations to manipulate, each location has to be linked to one or more locations of the 3D model, thus allowing overall control of its shape.

Input device to physical model input In the second module, the actions performed by the user on the input device—and thus on the 3D model that it embodies—must be formulated in terms of an appropriate input for the physically-realistic deformation model. For example, if the input device provides the change of 3D positional and rotational information for different locations, and the physical model requires directional forces with their magnitudes, this module has to carry out the necessary conversions appropriately. In this particular case, one solution to express the displacements as forces (as required by the physical model) is to assign an arbitrary reference material to the input device.

Physical model output to 3D model The third module analyzes the results of the physical simulation and extracts relevant information to update the 3D model's geometry.

Of course, for continuous deformations the interaction loop invokes these two last modules repeatedly. Note that in the case of associating the input device with only subparts of the 3D model, we would have to loop through all three modules.

4 First prototype and proposed interaction metaphor

Based on the design principles, we developed a prototype that presents concrete choices for the three components and three interaction modules. Note that our prototype is conceived as proof-of-concept, and thus we limited this first version to simple deformations on simple objects made out of homogeneous materials. Hereafter, the homogeneous materials are described by their stiffness E.

4.1 The chosen components

For the *3D model* of our example, we consider a beam that is fixed at one end and a force in a vertical direction that is applied at the other end.

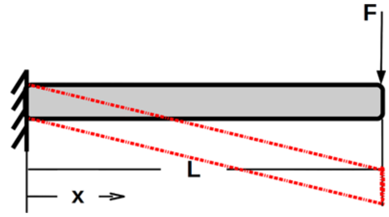


Fig. 2 A beam fixed at its left extremity. A force in a vertical direction is applied at the right extremity

For the *input device*, we decided to use the ShapeTape (Fig. 1), an array of fiber optic sensors fixed on a thin malleable strip of metal coated in plastic for protection. Our version measures 32 cm × 1.8 cm × 0.8 cm. The sensitive area is delimited by two colored bands; it contains 16 sensors arranged in 8 pairs. Bending and twisting the sensitive part of the tape modulates light through the fibers. The locations of variations in light intensity are captured and used to calculate the 6DOF (six degree-of-freedom) Cartesian data (x, y, z, roll, pitch, and yaw) for each segment of a strip. This data can be interactively used for constructing a 3D model that closely reproduces the form taken by the tape.

There are two main reasons why we chose ShapeTape as the input device: first, this device is beam-shaped, and thus its affordance naturally invites users to employ their hands to bend and twist it. Second, it operates at interactive rates due to high-speed data acquisition from the sensors.

For the *physically-based deformation model*, we integrated a linear physical model that handles small deformations. More precisely, our physical model simulates beam-shaped flexures [18].

Recall that the beam is fixed at its left extremity ($x = 0$) and a vertical force F is applied at its right end, as illustrated in Fig. 2. The result of a solid mechanics computation can be obtained either in terms of force values or in terms of displacements, depending on the formulation we choose for the boundary conditions. Indeed, if we consider a given force as the input, the result will be the displacement of all the points in the beam. On the other hand, if the input is the displacement, then the result will be the corresponding force. The analytic solution that describes the displacement of our beam example is given by the following equation:

$$u(x) = \left(\frac{(x-L)^3}{6} - \frac{(L)^2}{2}x + \frac{(L)^3}{6}\right)\frac{-F}{E.I_z} + \left(\frac{(x-L)^4}{12} + \frac{(L)^3}{3}x - \frac{(L)^4}{12}\right)\frac{-m.g}{2E.I_z.L} \qquad (1)$$

where:

- $u(x)$ is the y-displacement at a given x location of the beam,
- F is the applied force,
- L is the length of the beam,

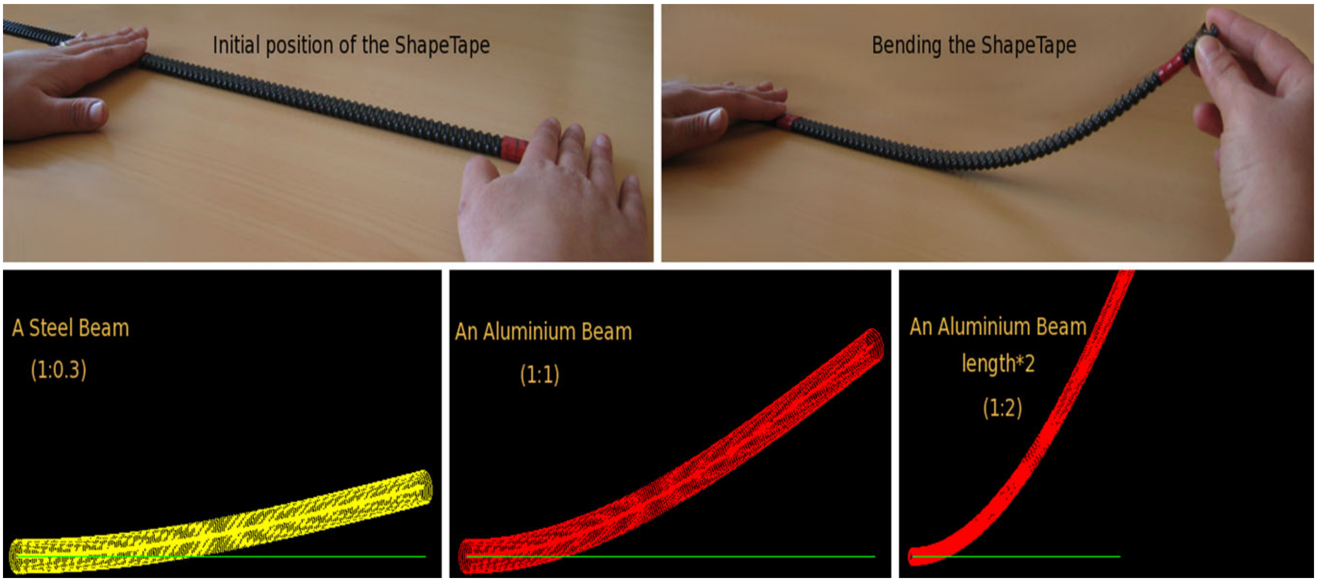


Fig. 3 A physically-based beam bending, controlled interactively by the ShapeTape. For the same tape displacement, the physical behavior of the beam changes according to the material (steel, aluminum) and the length. The *red color* means that the material breaks. In this example we assigned an aluminum material to the tape in order to calculate the force value corresponding to its displacement

- E is the Young modulus, that defines the stiffness of the homogeneous material,
- I_z is the inertial moment of the beam that depends on the geometry of its section,
- m is the mass of the homogeneous beam material,
- g is the gravitational constant.

It is important to highlight the fact that the aforementioned force generation method is applicable in both nonlinear deformations and composite materials. Nevertheless, an appropriate physical model needs to be integrated in order to take into account the new mechanical considerations.

In order to simulate the beam bending in our example, the tape is initially flat (Fig. 3, top-left). Then, with one hand, the user blocks movements on the left end of the sensitive part of the tape. With the other hand, the user bends the right end (Fig. 3, top-right).

4.2 The chosen interaction modules

Once these components are chosen, we have to link them together using the three interaction modules. In the first module, *3D Model to Input Device*, we have to map the information provided by the ShapeTape to the 3D model. Our version of the ShapeTape provides relative positions and orientations of 40 locations. In our simple prototype, we do one-to-one mapping of the right endpoint of the tape to the endpoint of the 3D model.

The challenging part of using the ShapeTape as an input device is the implementation of the second module, *Input Device to Physical Model Input*. This is because the ShapeTape does not capture forces that are required by physically-based deformation models. Hence, we have to somehow derive the forces from the tape's displacements. Our idea is to carry out the physical simulation in two steps. In the first step, we arbitrarily assign a homogeneous reference material with stiffness $E_{reference}$ to the ShapeTape, and we capture the movement of the tape's endpoint. The stiffness $E_{reference}$ of the reference material together with the displacement, the geometry and the boundary conditions are then inserted into the physical model. We obtain the associated force that would have to be applied to provoke this displacement. This force and the material of the object to be deformed, represented by its stiffness $E_{3Dmodel}$, are the input parameters for the physical simulation that is then executed in the second step in order to determine the new displacement of each point of the 3D model.

At this point, we want to make it explicitly clear that the choice of the arbitrary reference material is completely independent of the actual material the ShapeTape is made of. The only reason to introduce the reference material is to obtain a force that would have been necessary to displace the ShapeTape had it been made out of the reference material. In other words, a reference material with higher stiffness induces a higher force for the same displacement! The most natural choice for the reference material is to take the same material as the 3D model. However, for a more accurate interaction, it is sometimes interesting to under- or over-exaggerate the movement of the ShapeTape. In this case, a different reference material can be associated with the ShapeTape. For example, for a precise deformation of a very stiff material (such as steel), a less stiff material (such as aluminum) can be associated as a reference material with the ShapeTape, resulting in a higher amplitude of movement of the ShapeTape.

In both steps of our simulation process, we use (1) to compute first the applied force and then the displacement of each point of the beam under this force. In the first step of the simulation, to calculate the force value, we assign an arbitrary homogeneous reference material $E_{reference}$. Indeed, we only consider the displacement of the endpoint of the ShapeTape, so $x = L$ and $u(x) = u(ShapeTape_{endpoint}) = u(L)$. By referring to (1), the value of the force is computed as follows:

$$F = \left(u(L) + \frac{L^3 m_{reference}.g}{8E_{reference}.I_z}\right) 3E_{reference}.I_z.L^{-3}.$$

In contrast to the first step of our simulation process, we consider in the second step the real materiel characteristics of the beam to compute the y-displacement of each x point of the beam under the force F calculated in the first step, in accordance with (1).

The third interaction module, *Physical Model Output to 3D Model*, is easy to develop in our prototype since the output parameters of our physical model are directly the displacements of the points of the 3D model. Hence, we can directly use the new locations as the geometry of the 3D model.

As depicted in Fig. 3, for a given displacement of the ShapeTape associated with a fixed reference material with the stiffness $E_{reference}$, the behavior of the beam changes according to the 3D model's type of material (stiffness $E_{3Dmodel}$) and its geometry. Indeed, under the same bending force, an aluminum beam bends more than a steel beam with the same geometry since it has a lower stiffness. Similarly, as an example for different geometries, an aluminum beam that is twice longer deforms even more (Fig. 3, bottom-right). Of course, we can also change the reference material by varying the assigned stiffness $E_{reference}$. When the material no longer resists the applied force, the object breaks, as shown in red in Fig. 3 (bottom).

5 User study

In this section, we present the user study that we conducted to validate the prototype of our tangible user interface which follows the design principles presented. In particular, this user study aims to test whether the prototype correctly embodies the 3D model and whether it allows users to perform beam deformations, thus validating the proposed design principles. It is worth bearing in mind that the physically-based deformation is divided into two steps. First, the association of a reference material with the ShapeTape in order to convert displacements into forces, and second, the application of these forces to the 3D model of the beam. This two-step process compensates the absence of direct haptic feedback while still driving a physically-based deformation model that necessarily requires forces as input.

Consequently, besides testing the embodiment and usability of our prototype, another particular interest of our user study was to see whether this two-step process does not disturb users during deformation tasks since this is one of the main contributions of our work. As a result, we designed our user study in order to test the following three hypotheses:

Hypothesis H1: The ShapeTape embodies the virtual beam.
Hypothesis H2: Our prototype is usable for the deformation of a virtual beam.
Hypothesis H3: The deformation based on the two-step process does not disturb users during deformation tasks.

As we consider our prototype to be a good educational tool that favors the understanding of physically-based deformation behaviors, we decided to use engineering students as the subjects of our user study. The participants were students in the field of advanced engineering technologies at the ESTIA engineering school (École Supérieure des Technologies Industrielles Avancées—*School of Advanced Industrial Technologies*) located in Bidart, France. ESTIA is not specialized in mechanics, but aims to train generalist engineers with multiple skills in mechanics, electronics and computer science. NB. ESTIA students do not necessarily have the background in mechanics. During their first year students learn basic skills in mechanics, then more complex simulations are studied in the second and third years. 13 ESTIA students from the first and second years (average age: 26, standard deviation: 3.88 years) manipulated the ShapeTape to deforming the virtual beam made out of different homogeneous materials. For all 12 exercises, the users were told the reference material as well as the material for the virtual beam. Both materials were chosen from among the four following homogeneous materials: bismuth (stiffness of a 32 GigaPascal Young modulus), aluminum (69 GPa), stainless steel (203 GPa) and steel (210 GPa).

In each exercise the subjects were asked to precisely determine the minimum force value required to break the virtual beam or mechanically correct the force value required to pass the deformation into the plastic domain. As shown in Fig. 3, we showed the entry into the plastic domain by coloring the virtual beam in red. After each exercise we asked users to rate the degree of correspondence that they felt between the ShapeTape and the virtual beam. All the users accomplished the 12 exercises with different combinations of reference materials and virtual beam materials. To eliminate any learning effect, for each subject the order of the material combination was randomized. Depending on the similarity of the two materials, we divided these combinations into 3 categories:

Category IDENTICAL The reference material and the virtual beam material are identical
(e.g. $E_{reference} = E_{3DModel} =$ Steel).

Category SIMILAR Both materials are different but still have a rather similar stiffness value
(i.e. $|E_{reference} - E_{3DModel}| \leq 171$ GPa,
e.g. $E_{reference} =$ Steel, $E_{3DModel} =$ Stainless Steel).

Category DISTANT The stiffness values of the materials are considered as very different
(i.e. $|E_{reference} - E_{3DModel}| > 171$ GPa,
i.e. $E_{reference} =$ Bismuth, $E_{3DModel} =$ Steel).

Each of the 13 subjects had to operate 4 material combinations in each category, resulting in 12 exercises per subject and 156 trials in total for all the users. The analysis of these exercises has shown that the subjects were able to determine the force (within a tolerance range) required for passing the virtual beam into the plastic domain in 155 of the 156 trials. With such a convincing result, we can consider that all the subjects have accomplished their task, and without an inferential analysis, we validated the Hypothesis H3: The deformation based on the two-step process does not disturb users during deformation tasks.

For all three material combination categories, we evaluated the degree of correspondence that the users felt separately. Three pairwise analyses of variance (ANOVA) tests between the three categories showed that the difference in the degree of correspondence that the users felt is significantly different between all three categories (IDENTICAL vs. SIMILAR: ($F_{1,102} = 34.50$, $p < 0.0001$), SIMILAR vs. DISTANT: ($F_{1,102} = 34.23$, $p < 0.0001$) and IDENTICAL vs. DISTANT: ($F_{1,102} = 194.01$, $p < 0.0001$)).

Furthermore, for the IDENTICAL and SIMILAR categories, users stated that they felt a good or perfect correspondence between the ShapeTape and the virtual beam, and the significance of this statement was confirmed by a one-tailed paired t-test ($t = 7.11$, $p < 0.0001$, $df = 103$). On the other hand, for the DISTANT category, the users rather significantly declared a lack of correspondence ($t = -7.53$, $p < 0.0001$, $df = 51$). However, based on our results, we can validate the Hypothesis H1 for the IDENTICAL and SIMILAR categories: The ShapeTape embodies the virtual beam.

At the end of the exercises, the users filled out a written questionnaire. All users agreed that they were able to deform the virtual beam with the ShapeTape. 12 subjects (92 %) found that our prototype was efficient for the virtual beam deformation task (Confidence Interval: $CI[62\ \%, 100\ \%]$, $p = 0.05$). Moreover, 11 subjects (85 %) found that the use of our prototype offered an interaction that is closer to reality than what they would have been expecting by using a mouse ($CI[54\ \%, 100\ \%]$, $p = 0.05$). Hence, we validated the Hypothesis H2: Our prototype is usable for deforming a virtual beam.

The assessment from a more subjective point of view showed that 100 % of the users found our prototype pleasant to use. In order to measure the user's feelings, we presented the Geneva Emotional Wheel [15] at the end of the experiments. 11 subjects (85 %) found using our prototype interesting and 2 users (15 %) felt happiness. This is very positive feedback about the acceptance of our prototype.

Besides the 12 exercises above, where the reference material was fixed, we ran another experiment where the subjects had to choose the reference material themselves in order to observe their intuition about our two-step process. More precisely, we fixed the material of the virtual beam, then the subjects had to choose the reference material that best fitted the deformation out of a given set. 90 % of the participants chose the best corresponding reference material, which had the most similar (or the same) stiffness with regard to the beam material. This is significant according to the paired t-test when comparing to a 50 % average ($t = 8.95$, $p < 0.0001$, $df = 12$) and we experimentally concluded that the design principles we followed for our prototype made it intuitive. Finally, observation during the user study showed that some users would have liked to play around with the reference material in order to improve the precision of the interaction. This is an interesting perspective that we plan to explore in the future. Indeed, different material stiffness may lose embodiment, but this can enable new possibilities in terms of interaction.

6 Tangibility of our prototype

As explained above, the proposed prototype considers a physical model and gives users the feeling that they are literally taking the object in their hands. This is our major contribution with respect to previous work: physically-realistic deformation and the embodiment of the virtual shape in a physical device.

Let us now analyze the tangibility and embodiment of our prototype. First, in order to analyze the link between the tangible and the digital object, and thus provide a better understanding of the interaction metaphor, we classify it within the framework of Koleva et al. [9]. The *degree of coherence* between the physical object, the ShapeTape, and the digital object, the beam-shaped 3D model, is quite good since it is in the proxy category, which is level 4 of the coherence continuum that ranges from weak (level 1) to strong (level 6). The *transformation* is rather literal (movement on physical object will result in the same movement on the 3D model), while the *lifetime of link* is permanent. The *autonomy* is full because the existence of the digital object is not related to the existence of the physical object (and vice versa). The *cardinality* of the link is a common one-to-one relationship. Indeed, the tape is coupled with a single beam-shaped 3D model. Obviously, the *source of the link* is the physical object since the tape mediates the transformations to the beam-shaped 3D model. Finally, the *sensing of interaction* are flexions in two orthogonal directions, and torsion along the tape's axis.

Second, we classified our prototype according to the taxonomy of Fishkin [5]. Our interaction technique respects the *metaphor of the verb* because the movement of the user interface corresponds to the expected movement of the 3D model. In our simple beam example, the *metaphor of the noun* is respected as well. However, by extending our interaction metaphor to more sophisticated 3D models and by mapping the tape to, for example, parts of the medial axis of a tubular-shaped 3D model, we would lose the metaphor of the noun. Furthermore, due to the distance between the action space and the perception space, our application has distant embodiment according to Fishkin's taxonomy.

At the moment the only possible manipulation is at the endpoint of the tape. Obviously, this is not enough for allowing the user to carry out complex deformations. We are currently working on how to extend our interaction metaphor to take into account the entire potential of the ShapeTape:

- In order to perform deformations of more complex tubular objects rather than just a straight beam, we believe that rigidifying the ShapeTape is necessary for the *3D Model to Input Device* module in order to make the shape of the input device correspond with the shape of the 3D model, according to the principle of fully embodying the entire 3D model.
- The ShapeTape's coordinates are calculated incrementally starting from the origin of a local coordinate system. Consequently, when we move the entire tape, the displacement is not detected, breaking the system's immersion through a lack of visual feedback. To solve this problem of absolute positioning in space, the ShapeTape can be combined with 6 degree-of-freedom position sensors to place it in the global coordinate system.

Finally, it is worth noting that our prototype would scale to other shapes/objects. Indeed, our approach based on our design principles could be generalized to a wider range of shapes and physical input objects. The embodiment depends on having a physical input object with a similar shape and behavior as the virtual object. For a more versatile manipulation, we could embody subparts of the 3D model in the input device, with a slight loss of embodiment. Since certain successive association steps between the user interface and the subpart of the 3D model become necessary, they, however, break the immersive character of the deformation.

7 Conclusion

In this paper we have presented principles for designing tangible user interfaces for physically-based deformation. These design principles favor the embodiment of the entire 3D model by the user interface, but they can also be used to embody only a subpart of the 3D model.

Based on these principles, we designed a first fully functional prototype: we used the affordance of a passive tangible deformable input device, the ShapeTape, that allows intuitive two-handed bending and twisting gestures. The user applies force directly on the tape and the actions are then formulated in terms of the input of the physical model.

By means of a user study, we validated our approach for linear bending of simple beam-shaped objects. In the near future we intend to study how to map the passive tangible user interface to more sophisticated 3D models. We are also considering expanding the tangible metaphor to other types of deformations such as torsion, traction or compression. In addition, we plan to integrate a reduction order model approach which has the potential to make it possible to provide real-time nonlinearities in kinematics.

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