Morphees: Toward High "Shape Resolution" in Self-Actuated Flexible Mobile Devices

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Figure 1. Morphees are self-actuated flexible mobile devices that adapt their shapes to offer better affordances. (a) E.g a mobile device can shift into a console-like shape by curling two opposite edges and be easily grasped with two hands. Among the six strategies we built to actuate Morphees, here are two high-fidelity prototypes using Shape Memory Alloys (SMA): (b) one using projection and tracking on wood tiles that are actuated with thin SMA wires; and (c) one directly bending a flexible touchscreen (E-Ink and Unmousepad) by using (d) SMA wires that we educated (forged) to remember the shape we needed.

ABSTRACT
We introduce the term *shape resolution*, which adds to the existing definitions of screen and touch resolution. We propose a framework, based on a geometric model (Non-Uniform Rational B-splines), which defines a metric for *shape resolution* in ten features. We illustrate it by comparing the current related work of shape changing devices. We then propose the concept of *Morphees* that are self-actuated flexible mobile devices adapting their shapes on their own to the context of use in order to offer better affordances. For instance, when a game is launched, the mobile device morphs into a console-like shape by curling two opposite edges to be better grasped with two hands. We then create preliminary prototypes of *Morphees* in order to explore six different building strategies using advanced shape changing materials (dielectric electro active polymers and shape memory alloys). By comparing the shape resolution of our prototypes, we generate insights to help designers toward creating *high shape resolution Morphees*.

Author Keywords
Shape resolution, organic user interface, shape changing, flexible touchscreen, haptic feedback.

ACM Classification Keywords
H5.2 [Information interfaces and presentation]: User Interfaces - Graphical user interfaces, Input devices and strategies, Haptic I/O.

INTRODUCTION
There are a growing number of shape-changing devices [20, 39, 42, 51]. However, most research has focused on demonstrating point-designs, i.e. illuminating a spot, in the space of possible shape-changing devices. We have reached a point in the evolution of these devices where it is necessary to be able to articulate how the devices compare and contrast with each other. If we take the analogy of a display device, we can express (and thereby compare and contrast) new display devices in terms of the number of pixels available, the pixel density, the screen size, screen refresh rate and number of bits per pixel. This tuple provides a rich space within which we can situate the different display devices built and identify gaps in the innovation cycle.

In contrast, we have no equivalent metric to describe shape-changing devices. Hence it is not clear how one prototype differs from another or what opportunities exist for new devices in this landscape. To address this gap, we introduce *shape resolution,* a tuple with ten features that we derive from Non-Uniform Rational B-splines (NURBS), a geometrical model able to describe most shapes. These features such as *Area, Closure and Zero-crossing* describe the features of a shape and also explain why they are desirable in a shape-changing device.

To explore a portion of the large design space that our framework offers, we propose and study the concept of *Morphees*, the next generation of flexible mobile devices that adapt their shapes on-demand to better fit the myriad of services they are likely to support. *Morphees* allows users to download applications that embed a dedicated form factor, for instance the "stress ball app" collapses the device on itself, or the "game app" makes it to adopt a console-like shape (Figure 1a).

We concretize our concept of *Morphees* by implementing preliminary prototypes that help us to explore six building strategies using different shape changing materials. For instance one uses tiles of wood that are actuated with thin Shape Memory Alloys (SMA) wires (Figure 1b) and the other bends a flexible touchscreen (E-Ink and Unmousepad [43]) using SMA wires that we forged to return to the shape we needed (Figure 1c). We compare the *shape resolution* of each design strategies and generate insights into creating *high shape resolution* self-actuated flexible devices.

Our main contribution is to offer the first metric for comparing shape-changing devices in term of shape by introducing the term *shape resolution* and its definition in ten features. We also contribute the concept of *Morphees*, the next generation of self-actuated flexible mobile devices, and show six technological approaches for building them. By evaluating the *shape resolution* of these strategies, we present informative insights for builders toward creating *high shape resolution* shape-changing devices.

THE FRAMEWORK OF SHAPE RESOLUTION

Our definition of *shape resolution* is based on the model of Non-Uniform Rational B-splines (NURBS) and has ten features (Figure 2) that are analogous to the ones used for display resolution such as number of pixel, size of pixel, bit per pixel etc. However, *a high resolution* feature is not about maximizing its value but **maximizing the range of its possible values**. For instance, a shape has a *high-curvature resolution* if its surface has range of curvatures comprised between -π and π (concave to convex spike).

Our features complement Coelho's properties [7] that describe the technological properties of shape-changing devices. Examples include power requirement, ability to memorize new shapes, input stimulus such as voltage potential or ability to sense deformations. This approach differs from ours in that these properties describe the object material and not the possible shapes it can adopt. To give a simple analogy, a display resolution is given by features such as pixel count, screen size or bits per pixel but not features such as power consumption or display technology (e.g. LCD), that, even if useful, relate to the underlying technology. Our approach follows the same line than the display resolution definition while Coelho's approach informs the technological description of the device.

NURBS principle

Invented in the 70s, NURBS is the geometrical model used to represent shapes from straight lines, to conic sections to free-form curves. A way to understand it is to see the shape as a grid of **control points** (a mesh), with particles traveling across it to trace the surface of the shape. At any time t, the particles' positions are an average of all the control points that attract them. The attraction depends on other attributes: the **weights** that can be seen as the amounts of attraction each control point has; the **degree** of freedom that can be seen as the size of the attraction effect: the more degrees, the more control points affect the particles, thus flattening the overall surface (e.g. a NURBS surface of degree 1 is a combination of lines). The **knot vector** allows some control points to affect the surface more strongly than others by partitioning the time into intervals. By varying the relative lengths of the intervals, it varies the amount of time each control point affects the particles, thus creating a surface less smooth. When the knot vector contains several consecutive knots of the same value (knot-multiplicity), it forces the curve to go through the associated control point, and create a kink in the surface [21].

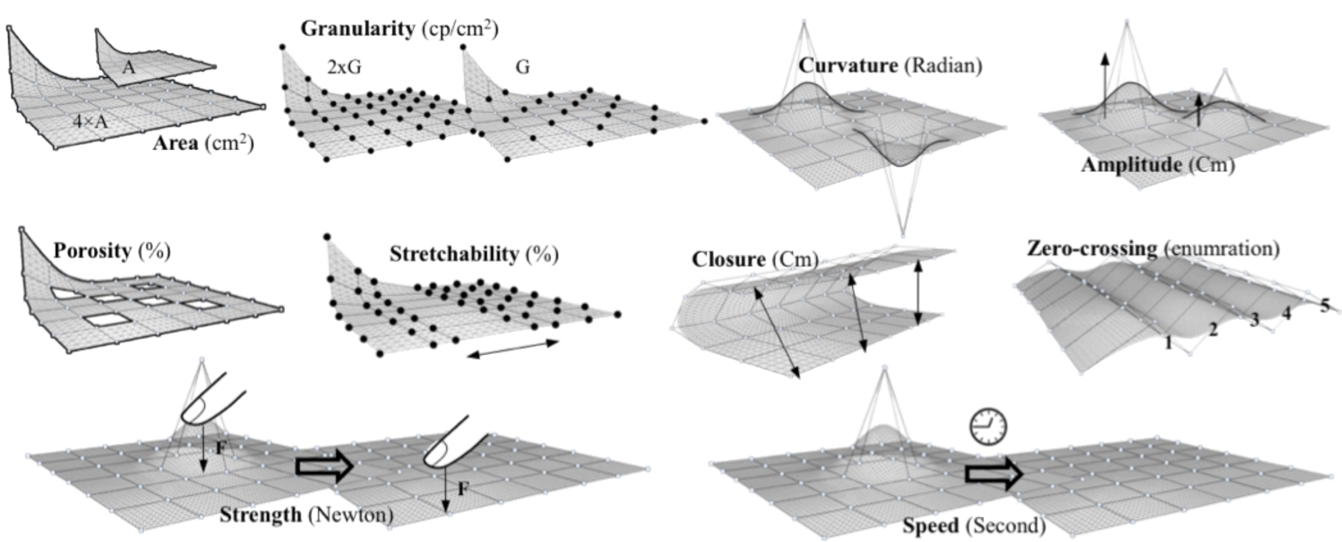

Figure 2. Summary of the 10 features of *shape resolution*. Contrary to the display or touch resolution, high resolution is not about maximizing each features, but rather maximizing the possible range of values.

NURBS can describe shapes but do not take into account physical constraints such as time, mass distributions, and internal deformation energies. Dynamic-NURBS [49] incorporates these and other physical quantities into the NURBS geometric equations. A detailed description of NURBS and Dynamic-NURBS can be found in [21, 49].

Simplified version of NURBS

The features of NURBS (control points, weight, degree, knot vector) are at a level of abstraction that does not help comparing shape-changing devices from a design perspective. At the same time, these models are powerful tools that can describe any shape. Given these arguments, our approach is to use a simplified version of NURBS and to extract features at a level of abstraction that is intuitive and descriptive to designers and practitioners. We choose to use a uniform weight across control points, with a fixed degree of freedom of two, allowing the creation of almost all possible shapes. By using a simplified version of NURBS, we lay down the foundation to extend our feature set in the future by using the complete NURBS model.

Advantages of using NURBS

There are other geometrical model for representing shapes (e.g. using volumetric representation) but we believe that NURBs model represents a good approach to describe topographies of deformable devices for the following reasons: (1) It gives a precise and uniform metric for computing the value of the features. For instance, a designer can easily compute them in a CAD tool (e.g. Maya deals with NURBs and a script can easily compute values for these features); (2) Its foundations are deeply rooted in the physical word: In the bygone days before computers, draftsmen (for shipbuilding) were drawing smooth curves using a splines, thin rods of flexible material held in place with lead weights called ducks (the equivalent of control points in NURBs); (3) It can accurately describe any shapes and thus allows us to explore a conceptual space, which not only copes with existing technologies but that also encompasses enhancements in material development.

THE TEN FEATURES OF SHAPE RESOLUTION

A way to understand the generation of our ten features is to see the shape as a mesh: a shape is made of (a grid of) control points as a display is made of pixels. Finding features is then describing the possible ways this mesh can deform. Our approach was first to list usual mathematical operations we can perform on a grid of points (e.g. area, angles, sum of angles, altitudes, distances etc.); secondly we generated the shapes created by varying these measures; finally we grouped shapes by similar characteristics that lead to our features that are illustrated in Figure 2 and for which we give the computation metrics in Table 1. In this section we define and illustrate them using the related work.

Our features work with both uniform and non-uniform shapes. With a uniform shape, the same values apply for each feature all over the surface, whereas with a non-uniform shape, the values of each feature are defined per part.

Area

The *Area* of the shape is its surface area. A way to approximate it is to compute the surface area of the mesh convex hull. With NURBS, it is equivalent to computing the surface area of the controls points since a NURBS surface is contained in the convex hull of these points.

There are several manually changeable *Area* devices. For instance Xpaaand [24] is a display that can roll on itself and that the user extends by pulling its edges ([90C m^2;720 Cm^2]). Actuated 3D construction kits such as Bosu [37], Topobo [41] or Kinematics [35] have a potentially infinite, extendable *Area* since users can always manually attach a new block to the entire assembly.

Automated changeable *Area* devices include large architectural structures [34, 1] and small systems such as the Inflatable Mouse [26]. The BMW kinetic sculpture [1] consists of balls hanging from a ceiling and moving vertically to create a shape. As the shape fits in a room, the *Area* varies from the surface of the floor to the surface area of the room itself. The Inflatable Mouse [26] is a relatively small device that inflates and deflates for ergonomic purposes. Its *Area* changes as a function of the pressure in a balloon placed inside. The maximum *Area* is nearly five times the minimum. A similar deformation is used in Ambient Life [15], where a mobile device has a soft casing that inflates to mimic breathing when air flows back and forth in it. Among his other works on shape changing devices, Hemmert also propose a device whose casing tapers downwards when held in hand, thus increasing its *Area* by a factor of ~3 (the back plate tilts by 10° into each direction, extending by up to 15mm in depth) [16].

Name	Type, unit	Computation
Area	[$\mathbb{R}^+$] (cm^2)	surface area of the total convex hull
Granularity	[$\mathbb{R}^+$] (cp/cm^2)	number of control points / *Area*
Porosity	[0;$\mathbb{R}$;100] (%)	100×(Σ holes *Area* / *Area*)
Curvature	[-π;$\mathbb{R}$;π](rad)	angle between 3 consecutive control points - π
Amplitude	[$\mathbb{R}^+$] (cm)	distance between rest and actuated position of a point on the surface
Zero-crossing	[$\mathbb{N}^+$] (Enum)	Σ sign changes between each consecutive angles
Closure	[0;$\mathbb{R}^+$;100] (%)	100×(*Area*-boundaries *Area*) / *Area*
Stretchability	[-100;$\mathbb{R}$;∞] (%)	100×(final-initial) / initial distance between 2 control points
Strength	[$\mathbb{R}^+$] (Newton)	force to move a control point from 0 to max *Amplitude*
Speed	[$\mathbb{R}^+$] (Second)	time to automatically move a control point from 0 to max

Table 1. Metrics of the ten features of *shape resolution.*

Granularity

Granularity measures the density of physical actuation points. We assume that these physical actuation points have a 1:1 relation to NURBS control points and hence granularity is computed by dividing the number of control points (cp) by the *Area* of the shape in rest state.

Granularity is generally fixed. E.g. Surflex [6] (Figure 3a) or programmable blobs [53] are actuated materials with four control points. BMW kinetic sculpture [1] (714 metal balls, *Area* not given) has higher *Granularity* followed by actuated-pin displays. Such devices are made of an array of linear actuators that move up and down to create a shape above a plane. Examples include Popup [32] with a *Granularity* of 0.4 cp/cm^2 (4x4 pins on 64x64mm), FEELEX [22] with a *Granularity* of 0.063 cp/cm^2 (6x6 pins on a 24x24cm), Lumen [38] with a *Granularity* of 2.4 cp/cm^2 (13x13 pins on 84x84mm), Relief [28] with a *Granularity* of 0.07 cp/cm^2 (12x12 pins on 45x45cm).

To our knowledge there are no objects that change granularity on-demand, except actuated-pin displays that can simulate this by actuating groups of pins as one.

Porosity

The surface of a shape can be discontinuous or perforated. The related feature is *Porosity* and is the ratio of the *Area* of perforated parts to the total *Area* of the shape. Computing the surface areas in done by using the convex hull made by the control points of the perforated and non-perforated parts of the surface. Thus the porosity can be computed by the following formula: 100×(Σ holes *Area* / *Area*).

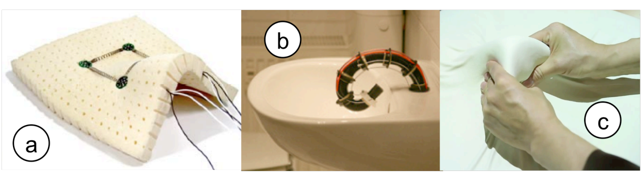

Figure 3. (a) Surflex is an actuated material whose mesh is base on four control points; (b) The trinity Faucet has a null *Zero-crossing*, it can curl on itself; (c) ClaytricSurface is a surface, filled wit Polysterene balls, that can increases its *Strength* by sucking air out of the material.

Changing the *Porosity* of a material is difficult since this deformation is not homeomorphic, i.e. not a result of a continuous stretching or bending of the original shape. Thus it is necessary to pre-perforate the material and close the hole when needed. This mechanism has for instance been used to create automated blinds to regulate the flow of air and light. Examples include Homeostatic facade [57] which *Porosity* goes from 0% to theoretically ~90% or Shutters [5] which *Porosity* goes from 0% to ~50%.

Curvature

The *Curvature* intuitively describes the curviness of the surface. It is computed by removing π from the angle between 3 consecutive control points. Thus, the *Curvature* is positive for convex shapes, negative for concave shapes and zero for planes. For instance, a unit sphere has π/2 *Curvature* since the control points of a sphere form a cube.

Examples of fixed *Curvature* devices include spherical devices (*Curvature* π/2) such a Sphere [3] and FlyEye [55], or arc shapes (Curvature also ~π/2) such as pointing devices proposed in Mouse 2.0 [52].

There are manually changeable *Curvature* devices such as Speakup [58] that changes its shape from convex to concave. Note, however, that curve deformations are not trivial due to the intrinsic properties of material: a non-stretchable plane cannot be deformed into a sphere. Such planes may be deformed into cylinders. This is seen in Gummi [45], a thin touchscreen device that users can manually and continuously bend in one dimension. Other devices using E-ink flexible touchscreen allowing similar deformations include the PaperPhone [27], DisplayStacks [11] or FlexCam [8]. Bookisheet [54] reports a maximum bending of ± π/2 that corroborates our own measures using an 8x10cm E-ink display. Curving more than the material limits causes damage. In order to increase the maximum *Curvature*, alternative materials have to be considered, for instance paper as in Paper Window [18].

Finally, few works have investigated automated changeable *Curvature*. Haptic Chameleon [30] is a widget for navigating video that changes shape depending on its functionality. For instance, when circular (*Curvature* π/2) it plays the video frame by frame, and when rectangular (*Curvature* 0 on each edges) it plays the video scene by scene. Harrison [13] demonstrates a touchscreen that creates bumps and valleys on a seamless surface. They created air chambers by layering several specially cut pieces of clear acrylic. A thin sheet of latex is draped on top. Inflating or deflating the cavities allows a *Curvature* range from -π/2 to π/2 for each cavity. A similar mechanism is presented in [46]. Reverse *Curvatures* (concave and convex) are also possible with Surflex [6] since it has actuators on both sides of a material (Figure 3a).

Amplitude

The *Amplitude* intuitively describes the range of displacement of control points. It is computed as the distance between the rest position and the actuated position of a point on the surface. For instance, a rigid plane has zero *Amplitude* and a unit sphere has an *Amplitude* of 1.

Examples of automated changeable amplitude include actuated-pin displays already presented earlier. For instance Popup [32] has a maximum *Amplitude* of 12cm, FEELEX [22] 8cm, Lumen [38] 6cm and Relief [28] 13cm. In comparison, BubbleWrap [3] or ShadePixel [25], that are also actuated-pin displays, operate at a smaller *Amplitude* (<1cm) and are rather used to simulate texture on a surface.

Note that actuated-pin display are 2.5D, meaning that they have a planar base. But the computation of the *Amplitude* also applies for any 3D shapes. The shape on Figure 3b can be used to illustrate how to proceed: each visible joint being assimilated as a control point, the *Amplitude* is thus given by the altitude between each triplet of consecutive joints.

Zero-crossing

Zero-crossing describes the capability of a shape to have wave-like forms. It is the number of sign-changes between each pair of consecutive angles across the surface. A shape with a large *Zero-crossing* can have a wave pattern. A sphere has zero Zero-crossing. Note that there is a relation between *Granularity* and *Zero-crossing*; a high *Granularity* implies a possible high value for *Zero-crossing.*

There are few works investigating changeable Zero-Crossing devices. Harrison [13] demonstrates one of them with a touchscreen that creates bumps and valleys. When the touchscreen is flat the Zero-Crossing value is *null* but when air is pumped into the preformed cavities, the Zero-crossing reached a value that depends on the number of cavities; two in their example. With Pinoky [47] it is possible to increase this number. Pinoky is a ring-like device that can be attached to a plush toy for instance. By attaching the devices in several points of the plush and by alternating the direction of the actuation, it is thus possible to achieve variable *Zero-crossing*. However Pinoky has a low *Granularity* as the actuator are substantially large. Paik et al. demonstrate how to fold a surface into a set of shapes such as a boat or an airplane using the art of Origami [36]. Finally, the Thrifty Faucet [50] (Figure 3b) shows water consumption and hygiene to the user through deforming its shape into various postures. The Faucet can curl on itself or form a wave pattern (from zero to three Zero-crossing).

Closure

Closure intuitively describes how "closed" a shape is. It is computed as 100×(Area- boundaries Area) where boundaries *Area* is the surface area of the shape created by using the control points situated on the edges. A Plane has 0% Closure while a Sphere has 100% closure.

Thrifty Faucet [50] (Figure 3b) illustrates changeable *Closure*. The Faucet is flat at rest and can form a spiral when actuated. Topobo [41] also achieves this circular deformation. Tilt display [1] illustrates an actuated-pin display with higher *Closure* than other pin-displays: the screen placed on each pin can tilt, thus offering control over the *Closure* of the shape. Finally, Qi [40] demonstrates how to curl and flip pieces of paper on themselves by sewing Shape Memory Alloy directly on them.

Stretchability

Stretchability describes how much the surface distorts between two control points. It tells how far apart (stretching) or close (compressing) two control points can move. It is computed as $100\times(d_{final}-d_{initial})/d_{initial}$ where d_{final} is the final distance and $d_{initial}$ the initial distance between two control points. 0% means that a shape is not stretchable. A purely compressible shape has a negative *Stretchability* value up to -100% and a purely stretchable shape has a positive value limited by the physical characteristics of the material.

Shape changing objects relying on solid materials have a fixed *Stretchability* of 0%. Inflatable devices have a fixed positive *Stretchability.* For instance the Inflatable Mouse [26] (~500%), Ambient Life [15] or inflatable buttons [13].

An example of a device with changeable *Stretchability* is Mudpad [23]. It is a surface that can change viscosity under the effect of an electromagnetic field in order to provide haptic feedback. The viscosity levels range from low viscocity fluids like water to highly viscous peanut butter. The liquid is embedded in a latex casing that can be deformed when users are pressing the surface.

Strength

The *Strength* is the force needed to move a control point from the minimum *Amplitude* position to the maximum *Amplitude* position of the shape. Note that we define a difference in *Amplitude* as the reference point to compare *Strength* of devices. For instance a shape with a fixed high *Strength* is a rigid shape, i.e. it requires a large amount of force to deform (or break).

For decades, haptic feedback researchers have been investigating automated changeable *Strength* using device such as articulated arm. One example of manipulating physical shape with an articulated arm is the Haptic Chameleon presented earlier [30]. The changes in shape that the controller undergoes (circle to rectangle) create a force feedback (*Strength* is not specified).

Examples of haptic feedback devices are ClaytricSurface [29] (Figure 3c) or Jamming UI [10] that are surfaces filled with Polysterene balls. By changing the air pressure inside the box, the particles compress, thus changing the softness of the overall material. This mechanism, called jamming, provides high *Strength* and is used to allow robots to grab heavy objects. MimicTile [31] is a flexible actuator placed on the side of a device that can dynamically change it stiffness by using an assembly of Shape Memory Alloy (the nominal practical force produced is 150 gf). SqueezeBlock [12] enables eye-free interaction with a mobile device by altering the stiffness and size of the virtual spring. Dynamic Knobs [17] is a knob, placed on the side of a mobile phone, which alters it shapes so that the user can explore the phone status by touching it (no *Strength* values given).

Speed

The *Speed* is the time needed to move a control point from the rest position to the maximum *Amplitude* position of the shape under self-actuation. As with *Strength* the difference in *Amplitude* serves as the reference point to compare *Speed* of devices. To draw an analogy with displays, *Speed* can be seen as the refresh rate of a shape. Note that deformable-only devices such as bendable touchscreens (Gummi [45], PaperPhone [27], DisplayStacks [11] FlexCam [8] or Bookisheet [54]) are characterized by 0 *Speed*. In other words they are not self-actuated.

The range of *Speed* covered by shape changing devices depends on the actuator technology. For instance devices using thin SMA wires, such in Animating Paper [40] or Shutters [5], can change shape very quickly even so they do not investigate variable *Speed*. Actuated-pin displays based on motors allow for more control over the Speed. For instance the triggering speed of FEELEX [22] pins is 100ms. We did not find any values of variable *Speed* in the literature of shape changing objects we reviewed.

Summary of current related work shape resolution

We explained the ten features that describe the resolution of a shape and illustrated these features with existing related work. Based on this we observe that:

- Changeable *Area* devices are either very large and allow a large range of values, or small but only allow a small variation of *Area* (5 times for the highest resolution one).
- *Granularity* is still low for most hand sized devices, and there are no devices with changeable *Granularity*.
- Change in *Porosity* has not been widely studied. Existing works only include large *Area* devices (window blinds).
- There are devices with fixed or manually changeable *Curvature* but few have changeable *Curvature*.
- Few systems have investigated changeable *Amplitude*.
- Changeable *Zero-crossing* has not been investigated fully. To our knowledge there are no shape changing devices that allow a wide range of *Zero-crossing* combined with high *Granularity*.
- Changeable *Closure* has not been intensively investigated either, especially combined with high *Granularity*.
- *Stretchability* devices are not mainstream. In particular we found only one example of a device with automated changeable *Stretchability*.
- Haptic feedback research has investigated high *Strength* resolution. There are however a few small *Area* devices (mobile) providing high *Strength*.
- *Speed* has currently been investigated as a value to maximize but we did not find shape changing with variable deformation *Speed*.

In summary, we observe that work on shape changing devices have concentrated on increasing the shape resolution for specific features, but few combine multiple high resolution features. In particular we see several gaps: (1) there are no small *Area* and high *Granularity* devices with changeable *Zero-crossing* and *Closure*; (2) there are few devices that change their *Porosity* or *Stretchability*. This is probably due to the intrinsic limitations of materials that are hard to deform; (3) there are few small Area devices with high resolution *Strength*. The main issue is that force-feedback actuation is difficult to miniaturize, as it requires physical motors; (4) there are no devices with changeable *Speed*, i.e. that investigate the animation of the deformation (this corroborates with Rasmussen [42]).

MORPHEES: CONCEPT AND PROPERTIES

A *Morphee* is a self-actuated flexible mobile device that address the multiple affordance desired by any applications and transform itself into desired shapes. We envision that app stores can potentially evolve to give opportunities to developers to create practical applications with their specific form factors. Using the Norman's definition of affordance [33], we present two main properties that such devices offer.

Perceived affordance on-demand

A *Morphee* changes shape to suggest the way it should be operated. For instance, the two sides of a *Morphee* can curl outward to mimic a console, thus suggesting users to grab the device with two hands. In Figure 4b, the top edges of a *Morphee* curls inward when the user is typing a password, thus suggesting a private operation to others in the vicinity (e.g. when typing a password).

Actual affordance on-demand (tactile & force feedbacks)

A *Morphee's* physical properties change during the interaction to help users perform actions. In other words, it offers *tactile and force feedback*. For instance, in Figure 4b, the curled edge of a *Morphee* becomes a gun trigger in a shooting game, i.e. it offers resistance and a detent sensation when pushed by users. Figure 4c instantiates the inflatable buttons by Harrison [13]: the surface creates bumps and valleys to mimic a physical keyboard, thus helping the user to enter text.

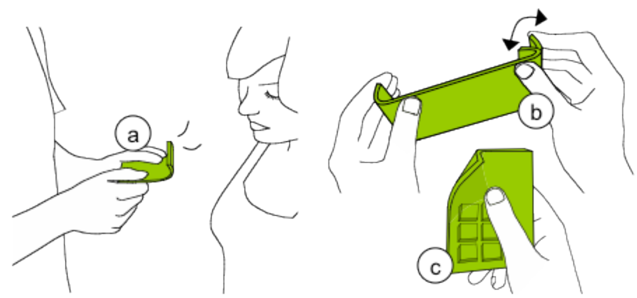

Figure 4. (a) The *Morphee* top edge bends inward to hide screen content to other users when typing a password. (b) a curled edge of the *Morphee* can be pushed to serve as trigger in a shooting game; (c) Bumps appear on the surface of the *Morphee* to mimic a physical keyboard to help the user typing.

Implementing Morphees

A Morphee has to be as thin and flexible as possible, with no physical switches or dials that could prevent shape deformations. It has several layers of flexible components: the computation circuits, the display and a 2D touch sensor and a shape-shifting layer. The shape-shifting layer morphs (and also senses its deformation), thus affecting the entire assembly. The key point is that the shape-shifting layer is a grid of physical control points, which can be actuated to form the desired shape. It implies that Morphees **physically instantiate our framework**. Actuating control points in the middle of the layer creates bumps and valleys while actuating control points in the periphery curl the layer. To realize these actuations there are various strategies possible, which we now investigate.

MORPHEES: SIX ACTUATION STRATEGIES

We compare six actuation strategies, five using advanced technologies in morphing materials: Dielectric Electro Active Polymers (DEAP) and Shape Memory Alloys (SMA). We start with the simple strategies and then progress to more complex and higher shape resolution strategies. For each strategy we present their principle of actuation and the prototypes we built. We then evaluate the strategy with the ten features we proposed to define the *shape resolution* (see summary in Table 2).

Morphee-motor: Linear actuation using motors

Principle: Morphee-motor is inspired by the SPIDAR system [44]: it uses motors and guitar strings to actuate control points. Actuating one motor decreases or increases the length between two corresponding nodes, thus bending the underlying part of the screen. The motor-strings couple is only placed on one side of the device so that strings do not prevent touch interaction when extended.

Low-fidelity prototype: The prototype shown in Figure 5a consists of two servo motors, two guitar strings and four control points on a 8x10cm sheet of plastic that has the same thickness than a flexible touchscreen (An E-ink flexible display being ~2mm thick and a flexible touch sensor ~1mm) and approximately the same flexibility. The strings are attached on diagonally opposite corners of the device. A set of 6 rings serves as guides for the strings along each diagonal (see a). When a motor turns in one direction it bends the screen inward, otherwise the screen goes back to its initial flat shape.

Shape resolution: The main advantage of Morphee-motor is the *Strength* it provides due to the motors. It also allows for high *Amplitude* and *Curvature*. One drawback of this approach is that increasing the *Granularity* of it would increase the number of motors needed and thus decrease the overall flexibility of the device. Also *Curvature* depends on the underlying material, a common issue we found recurrent with other strategies. A workaround is described in the section "Toward high resolution Morphees".

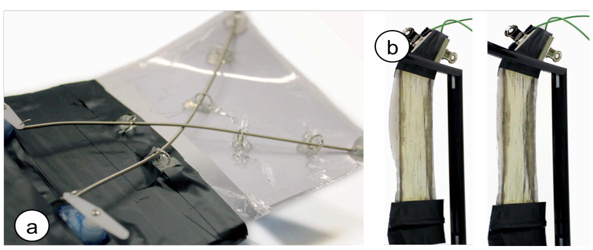

Figure 5. (a) Morphee-motor uses motors and strings to bend a piece of plastic that mimics the property of a flexible touchscreen. (b) Morphee-polymer uses Dielectric Electro Active Polymer to bend a sheet of paper.

Morphee-polymer: Linear actuation using DEAP

Principle: Morphee-polymer uses Dielectric Electro Active Polymers (DEAP). It consists of an elastomer sheet sandwiched between two electrode layers. When voltage is applied to the electrodes, electrostatic forces squeeze the sheet causing expansion in the perpendicular direction. Actuating the material decreases or increases the length between two corresponding nodes, thus bending the underlying part of the screen. The actuators are only placed on one side of the device so that the actuators do not prevent touch interaction when in their extended form.

Low-fidelity prototype: The prototype shown in Figure 5b consists of a sheet of polypower DEAP material (www.polypower.com) attached to a piece of classic paper (7×12cm). The actuation is done by using a switched-mode power supply that delivers voltages between 1000-2500V.

Shape resolution: The main advantage of Morphee-polymer is that *Granularity* can be increased without loss of flexibility. However it has less Strength, *Curvature* and *Amplitude* range, and it also has a fixed *Speed*. Lastly the power supply (~2500V) poses a challenge for miniaturization and safety.

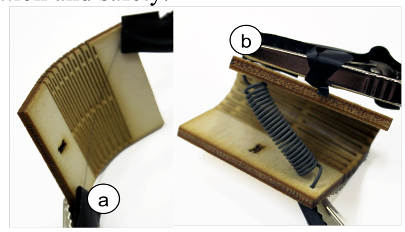

Figure 6. (a) Morphee-wire: It uses SMA in the form of wires. Here our prototype consisting of a flexible piece of wood. (b) Morphee-spring: It uses SMA in the form of springs.

Morphee-wire: Linear actuation using SMA wires

Principle: Morphee-wire uses Shape Memory Alloys (SMA) in the form of wires. SMA is a special metal alloy that "remembers" its original *educated* shape when deformed within limits, and returns to this *educated* shape when heated (70° to 90° C). SMA wires are special cases of SMA. They are educated to return to a smaller length than their original one (5% less length). A common way to actuate SMA is by passing current through them, which causes them to heat up. The actuators are only placed on one side of the device so that they do not prevent touch interaction when in their extended form.

Low-fidelity prototype: The prototype shown in Figure 6a consists of a piece of wood with a laser cut pattern allowing it to bend. Each edge of the wood is linked to a 0.06mm diameter 7cm SMA wire.

Shape resolution: Morphee-wire offers a reliable way to create a high *Granularity* shape. However, it does not provide enough *Strength* (more than Morphee-polymer), *Amplitude* or *Closure* as the wire can only shrink 5%. An alternative way is to use SMA springs (see Morphee-spring) or by combining it with a pulley system (see Morphee-sewn-wire). One advantage of using thin SMA wires is the *Speed* of the deformation (<1 second).

Morphee-spring: Linear actuation using SMA springs

Principle: Morphee-spring uses SMA springs which are educated to return to a compact spring when heated. As with SMA wires, a way to actuate them is to apply a voltage to heat them up. Because of their specific educated shape, SMA springs shrink more than wires. The actuators are only placed on one side of the device so that they do not prevent touch interaction when in their extended form.

Shape resolution: Morphee-spring provides more *Strength*, *Amplitude* and *Curvature* than Morphee-wire and Morphee-polymer. One drawback is the *Speed* that is quite slow (>1s second). In addition the springs are much thicker than actuators used in other strategies, this can prevent the creation of a thin flexible device. With our high-fidelity prototype, *Curvature* is affected in a similar way as in Morphee-motor.

Low and high fidelity prototypes: The first prototype (Figure 6b) consists of a bendable piece of wood (3mm). Each edge is linked to a SMA spring (1mm diameter wire and 5mm diameter for the spring). As springs shrink more than wires, we built another prototype with higher *Granularity* using a grid of 9 springs. We coupled springs with a Darlington pair transistor, which acts as a current driver and was controlled through an Arduino board.

Morphee-forged: "Home-educated" SMAs

Principle: Morphee-forged uses SMA wires that bend to a certain angle. This mechanism is possible by educating the SMA wires as bent shapes and to attach them to the device. When cold the wires are straight but when heated they bend. The set up is **reversible**: it is possible to place educated SMA on both sides of the device, as their deformation will follow the deformation of the screen.

Low and high fidelity prototypes: The low-fidelity prototype (Figure 1a) consists of a piece of wood with flexible edges. We attached two educated SMA to each edge to allow them to curl. The high-fidelity prototype (Figure 1c) combines an E-ink display (2mm thick) with an unmousepad touchsensor [43] (1mm thick). We attached our educated SMA to the devices using heat-insulated tape. The device can thus be in two shapes: flat or cylinder. Off-the-shelf SMA are educated to a certain shape (shrinking in size, springs, or straight shapes) but it is possible to educate them by heating (>500° C). We thus used SMA wires (1mm thick) that we maintained in the appropriated shape we needed while heating them up using a propane gas stove.

Shape resolution: Morphee-forged has advantages over other strategies. It allows concave and convex *Curvatures*, multiple Zero-Crossing and strong *Strength* and *Amplitude*. One drawback is the *Speed*: as it uses relatively thick SMA, the heating time is longer (the resistance of the wire is larger), thus increasing the actuation time.

Morphee-couture: Wood structure sewn with SMA

Principle: Morphee-couture uses the same SMA wires than Morphee-wire. The difference is that the wires are sewn into a tiled structure with inter-locking edges. The special pattern shown in Figure 7 acts as a lever that multiplies the shrinkage to give large actuation (5% shrinkage gives 90º bend). Note that the tiled structure is made of heat resistant material and that we added metal crimps in each hole to avoid the SMA burning the wood. The set up is **reversible**: inverting the pattern allows bends in the opposite direction.

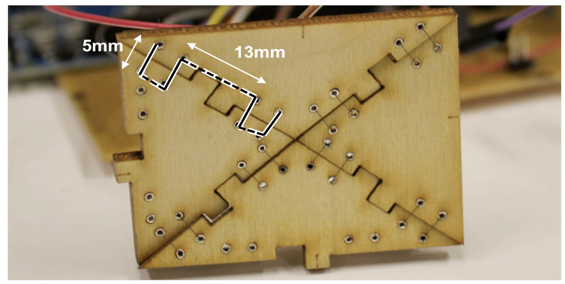

Figure 7. With the Morphee-couture, the sewing pattern allows to gain more from the SMA wires, i.e. that it allows each pieces of wood (3mm thick) to bend at 80º.

High-fidelity prototypes: Our prototype (Figure 1b) is based on a structure of 8 wood tiles. We coupled each wire with a Darlington pair transistor, which acts as a current driver and was controlled through an Arduino board. Using a projector we implemented three applications to illustrate *Morphees*: (1) one that bends the top of the device toward the user to hide the screen content; (2) one that bends the four corners in the same fashion that a flower blooming or closing; (3) one that actuates any hinges that users choose.

Shape resolution: Morphee-couture has numerous advantages over the previous strategies. It allows for concave and convex *Curvature* as well large *Amplitude*. It has a faster *Speed*, but less *Strength* than Morphee-forged.

Feature	Morphee-motor	Morphee-polymer	Morphee-wire	Morphee-spring	Morphee-forged	Morphee-couture
Area	54cm^2 (9×6cm)	84cm^2 (7×12cm)	20cm^2 (5×4cm)	p1: 20cm^2(5×4cm) p2: 80cm^2(10×8cm)	p1: 42cm^2 (6×7cm) p2: 70cm^2 (10×7cm)	80cm^2 (10×8cm)
Granularity	0.15 cp/cm^2 (8cp)	0.04 cp/cm^2 (3cp)	0.15 cp/cm^2 (3cp)	p1: 0.15 cp/cm^2 (3cp) p2: .23 cp/cm^2 (18cp)	p1: .14 cp/cm^2 (6cp) p2: .04 cp/cm^2 (3cp)	0. 45 cp/cm^2(36cp)
Porosity	0%	0%	0%	0%	0%	0%
Curvature	[0;π/8] can be increased with DC motors	[0; π/12], limited by maximum voltage for DEAP material	[0; π/12] limited by SMA	p1: [0; π/2] p2: [0; π/12] limited by SMA	p1: [-2π/3; 2π/3] p2: [-π/2; π/2] limited by SMA	[-2π/3; 2π/3] limited by SMA
Amplitude[1]	[0;6cm]	[0;1cm]	[0;0.5cm]	p1: [0;2cm] p2: [0;2cm]	p1: [0;1.5cm] p2: [0;3.5cm]	[0;4cm]
Zero-crossing	0. Actuators only on one side	0. Actuators only on one side	0. Actuators only on one side	0. Actuators only on one side	0	[0;3]
Closure	[0;6.2%]	[0;4.2%]	[0;10%]	P1: [0;50%] p2: [0;15%]	P1: [0;56%] p2: [0;55%]	[0;25%]
Stretchability	0%	0%	0%	0%	0%	0%
Strength[1]	170gf	50gf	150gf	500gf	500gf	150gf
Speed	0.5s, variable Speed depending on motors	0.04s depends on charge time	[1s;3s] depends on SMA heat-up and cool-down times	[1s;5s] depends on SMA heat-up and cool-down times	[1s;3s] depends on SMA heat-up and cool-down times	[1s;3s] depends on SMA heat-up and cool-down times

[1] Limits on values are similar to ones described for Curvature

Table 2. Evaluation of the 10 features for the prototypes we built using the six-actuation strategies we explored.

TOWARD HIGH SHAPE RESOLUTION MORPHEES

By evaluating our prototypes we gathered insights to help future builders. There are three main challenges to consider. First at the shape level, it is hard to have all features with high resolution. Secondly we discuss device's life cycles and the possibility of creating bistable devices. Finally, we argue that it is difficult to combine high shape resolution with high display and touch resolution.

High shape resolution

As demonstrated with our prototype and the examples from the related work, it is difficult to create devices with high resolution for all features. E.g. we need to optimise the compromise between *Curvature*, *Strength* and *Speed*: SMA wires are fast to actuate but have less *Strength* and *Curvature*. Morphee-couture offers a way to overcome this issue using a pulley system. It however does not increase the *Strength*. In comparison, Morphee-forged offers large *Curvature* and *Strength* but is much slower.

The tradeoffs between features are not specific to shape resolution, but also apply to display resolution. E.g. It is hard to create displays with a high refresh rate, high pixel density, high bits per pixel etc. For shapes, each feature is likely to be more important than others in various context. For instance a device with high *Strength* can be adapted for force feedback applications, while a device with high *Speed* can be used to create animated shape notifications to users. The choice of the device shape changes has thus to be dictated by the range of applications it can support, therefore maximizing the resolution of specific features.

Figure 8. Bistable shape can be achieved using heat deformable plastic.

Device life cycle and bistability

Another challenge is the life cycle. Maintaining a device in a shape requires the material to be constantly on, drawing significant power. In addition, shape-changing materials have a life cycle as well. They can potentially be triggered hundreds of thousands of times. But if the strain overcomes a certain ratio (depending on the material), it reduces their life cycle. For example we experienced this phenomenon with home-educated SMA: we educated some SMAs in a 90° bending shape and actuated them several times to test it. During the process we manually unbend the wire several time to force it to form a line. This caused a lot of stress in the material, thus reducing its life cycle. After several actuations, the SMA was only able to bend at 45°.

One solution is to use bistable materials. Similar to a bistable screen that can stay in one state when no power is provided (E-Ink), a bistable device can stay in one shape when no power is provided. A way to achieve this is to use heat deformable plastic (Figure 8) that becomes malleable when heated, and retains their shape when cooling down. Another example of bistable structure has also been proposed in the shape memory polymer chair [9].

High shape-display-touch resolution

Another big challenge is to combine high resolution for the shape layer but also for the display and touch ones. However, this is difficult given that the flexibility of the display and touch sensor will impact the way the shape layer can deform. As we experienced, the E-ink flexible display is quite stiff and reduces the possible Curvature that the device can have. A way to alleviate these issues is to use projection and tracking as in our Morphee-couture and as suggested in a recent vision of mobile computing [14]. In this case the display and touch layer does not add any constraint on the shape-changing layer. Another way to overcome this issue is to consider tiling the touch sensor and display as in the tiles of Morphee-couture.

Another issue is that the deformation can impact the data retrieved by the touch sensor. For instance, bending a resistive touch sensor is likely to trigger touch events while no fingers are in contact as it relies on pressure. The same problem would happen with optical sensing or TDR [56]. Thus the touch sensor technology has to be appropriately chosen to avoid this phenomenon. For example this is possible with capacitive touch sensing as used in Mouse 2.0 [52]. Some resistive technologies are also promising, such as TactileTape [19] that supports bends up to 85° .

CONCLUSION

In this paper we contributed a new metric to define the resolution of an interactive device: in addition to display and touch resolution, we proposed "shape resolution". We believe our work lay down the foundation for creating future high shape resolution devices. One example of such devices is our concept of *Morphees*, self-actuated flexible mobile devices that can change shapes on their own to offer better affordances. We envisage *Morphees* to be the next generation of mobile devices, with which users can download applications with their own form factor. In future work we are thus interested in building higher shape resolution *Morphees* by investigating further the flexibility of materials. We are also interested in exploring other kind of deformations that our prototypes did not yet explore, such as *Porosity* and *Stretchability*.

ACKNOWLEDGEMENTS

This work has been supported by the EC within the 7th framework programme through the FET Open scheme under grant agreement no. 309191.

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