Morphees+: Studying Everyday Reconfigurable Objects for the Design and Taxonomy of Reconfigurable UIs

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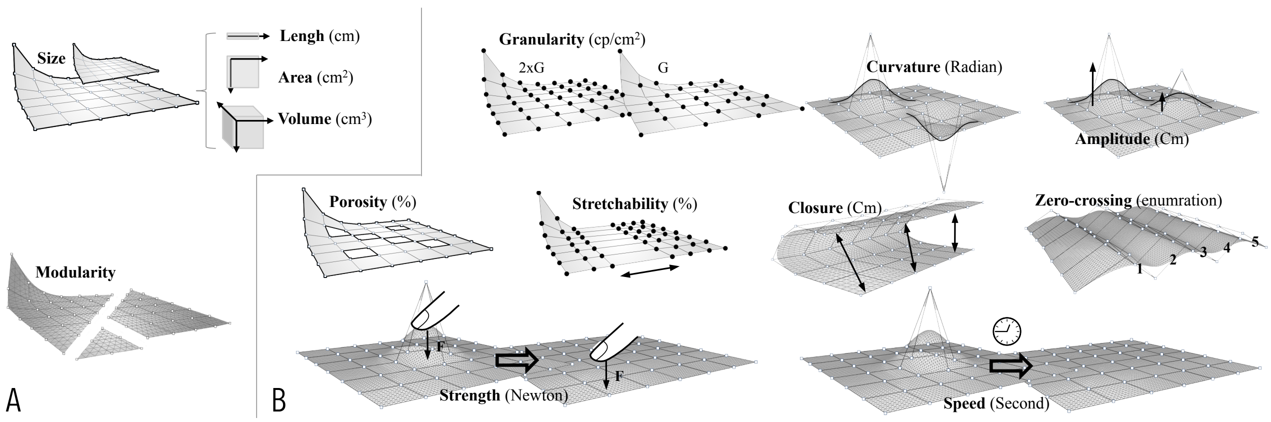

Figure 1. Refinement of the Shape Resolution features after analyzing daily deformable objects. We add (A) Size and Modularity to complete the (B) previous features. Size is an extended feature from the original definition of Area. Modularity is a new feature measuring the ability to be split into several parts that can be recombined.

ABSTRACT

Users interact with many reconfigurable objects in daily life. These objects embed reconfigurations and shape-changing features that users are familiar with. For this reason, everyday reconfigurable objects have informed the design and taxonomy of shape changing UI. However, they have never been explored systematically. In this paper, we present a data set of 82 everyday reconfigurable objects that we collected in a workshop. We discuss how they can inspire the design of reconfigurable interfaces. We particularly focus on taxonomies of reconfigurable interfaces. Taxonomies have been suggested to help design and communication among researchers, however despite their extensive use, taxonomies are rarely evaluated. This paper analyses two established taxonomies — Rasmussen's and Roudaut's — using daily reconfigurable objects. We show relationships between the taxonomies and area for improvements. We propose Morphees+, a refined taxonomy based on Roudaut's Shape Resolution Taxonomy.

Author Keywords

Taxonomy; Shape Resolution; Reconfigurable; Shape-changing; Deformable.

ACM Classification Keywords

H5.2 [Information interfaces and presentation]: User Interfaces

INTRODUCTION

Reconfigurable objects are objects that can be deformed manually by the user or have a system automatically actuate their shape. Shape-changing interface taxonomies [4,43,46] help describe the reconfigurability of interfaces and can be used to design new interfaces [26,35,44,52]. To date, there has been little effort to unify and strengthen these taxonomies despite shape changing interfaces continuously evolving. The taxonomies' descriptive power has been hardly tested, and it is uncertain if they are comprehensive and complete to describe all reconfigurations.

As a first step to sustain the taxonomies, we evaluate their descriptive power with end users' reconfigurable daily objects. We choose reconfigurable daily objects, as users are used to manipulating reconfigurable objects in their daily life, e.g., a knife-changeable blender to prepare a smoothie, a height-adjustable chair at work, a foldable ladder to reach the attic or an orientation-changeable light to read a book in bed. Their continuously evolved manipulations are handy for users (e.g., being able to open and close a folding fan with only one hand [28]). In addition, these objects have — explicitly or implicitly —

inspired the design and taxonomy of reconfigurable devices (e.g., [21,22,27,28,41,47,50,51]). Reconfigurable daily objects allow us not only to inform the taxonomy features that end users are used to, but also can inspire new reconfigurable interfaces.

We particularly focus on two taxonomies among previously suggested taxonomies. Roudaut *et al.* [46] proposed the term "shape resolution" which characterizes shapes as well as deformations in 10 geometrical features used to classify existing manual and automatic reconfigurable devices. Rasmussen et al. [43] presented a review of existing automatic reconfigurable devices and identified eight types of deformations to serve functional and hedonic design purposes. Both taxonomies are widely used within the HCI community [e.g., 26, 38]. Our goal is to study their ability to describe everyday reconfigurable objects, as these continue to inspire new interfaces.

In this paper, we systematically analyze 82 reconfigurable daily objects using two shape changing-interface taxonomies. We report our findings to improve the taxonomies and inspirations to design new reconfigurable interfaces. Our four steps approach provides the following contributions:

1. We collect 82 everyday reconfigurable objects [24] that are reusable by other researchers. The list includes pictures and descriptions. We conducted a collection and brainstorming workshop to have a set of objects.
2. Three authors classify the collected items using two taxonomies (Rasmussen's and Roudaut's) describing topological changes. We reveal the relationship between the taxonomies and areas for improvement.
3. We add Size and Modularity features to "shape resolution" taxonomy (Roudaut) which turned out to be the most complete and referenced taxonomy to describe shapes and deformations altogether.
4. To help designers, we also reveal how the reconfigurable features were implemented and discuss how to implement specific reconfigurable features using deformation mechanisms of everyday objects. Our goal here is to help to leverage daily objects deformations to propose new reconfigurable interfaces.

RELATED WORK

We report related work in the field of reconfigurable devices that either took inspiration from users' daily life or proposed design tools, mainly taxonomies.

Terminology

We define reconfigurable devices as devices with the ability to have multiple shapes and to be deformed manually (via user inputs) or automatically. Other words such as "deformable" [3,23,55,54,57], "malleable" [10,13,32], or "shape-changing" [4,10,35,43,46,56,58] have also been used to describe this concept. These words convey a change in shape, which means that there is an initial shape A and a final shape B. The transformation from A to B is called the deformation and can be initiated manually by the users (via molding [10], bending [12,50], twisting [47], etc.) or automatically by the system. This last category is also sometimes called actuated [30,39,42] or self-reconfigurable [48,59] interfaces. Most of the work presenting taxonomy focuses on automatic deformations (e.g., Coelho *et al.* [4] and Rasmussen *et al.* [43]). Roudaut *et al.* [46] cover both manual or automatic deformations.

Getting inspirations from users' everyday life

Along with Holman and Vertegaal's [16] vision of organic user interfaces that encourage designers to get inspiration from nature, many reconfigurable interfaces take morphologies from nature. Bamboostics [37] demonstrated bamboos bend toward passengers, as they are moved by wind. Some works explored biological motions [20] to express certain emotions of the interface. For instance, DEVA [7] presented excitement through ear wiggling, and Animate mobiles [15] moved up its head toward the user to show affection.

While nature-like interfaces convey certain feelings, interfaces using everyday objects tell designers how users interact with certain shapes. Alexander *et al.* [1] conducted a survey of 1515 electronic push buttons in home environments. They proposed a characterization of button properties and how this can inform the design of future reconfigurable devices and surfaces.

Reconfigurable daily objects tell users how to deform them as input. Lee *et al.* [28] investigated future foldable display using daily objects such as newspapers and umbrellas. Users change the size of the display by folding the map or turn off the display by completely folding the umbrella. Similarly, a sheet of paper [50], a piece of fabric [51], a book [21], an ancient scroll [22], a Rubik's Magic puzzle [41] and a Rubik's cube [47] were used to design deformable displays.

Considering existing reconfigurable objects enable researchers to use their affordance as well as quickly evaluate interactions with low-cost prototypes. It inspires us to take a closer look at reconfigurable daily objects. To our best knowledge, there is no systematic study on reconfigurable everyday objects. In this paper, we analyze the objects to inform the design of reconfigurable interfaces, in particular through the improvement of their taxonomies.

Taxonomy on shape-changing interfaces

As in most fields, early taxonomies often focus on technologies, as they are one of the first barriers for advancing the field. Coelho *et al.* [4] proposed such a taxonomy in which they describe the technological properties of shape-changing devices. Examples include power requirement, ability to memorize new shapes, input stimuli such as voltage potential or ability to sense deformations. This approach is technologically driven and describes the object material rather than the possible deformations.

Rasmussen *et al.* [43] present a review of 44 existing studies on shape-changing interfaces. They identify eight shape change taxonomy features with both topological and non-topological equivalent views, which has inspired other research on the design of features. Nørgaard *et al.* [35] presented eight interactive shape-changing toys implementing some of the features. They also analyze the toys to refine interaction properties of shape-changing interfaces. Kwak *et al.* [26] reported a repertory grid study that aims to describe the shape change features from the users' point of view by eliciting personal constructs about shape-change and focusing on understanding the feeling generated by different deformations. Rasmussen *et al.* [44] presented an analysis of sketches made by designers, focusing on a radio and a mobile phone, and, using on Rasmussen *et al.* taxonomy, they show which features are most often used in general or for certain devices (e.g., Spatiality used only for radio, Adding/Subtracting used only for mobile phone).

Roudaut *et al.* [46] propose the term shape-resolution that extends the definition of display resolution to shape-changing interfaces. It is based on the mathematical model of Non-Uniform Rational B-splines (NURBS) and has ten features that the authors used to classify shape changing prototypes from previous work. They also provide specific metric to compute them.

Troiano *et al.* [56] suggest four behavioral patterns of shape change from Sci-Fi movies. The authors collect 101 shape-changing instances from 340 movies and identified the functional behavioral patterns using thematic analysis. Note that our approach, although similar in motivation, differs significantly as we chose to look at concrete everyday objects whose shapes and deformations are already familiar to end-users.

In this paper, we evaluate Rasmussen's and Roudaut's taxonomies [43, 46], as they provide general views on shape change features (not just technology dependent or purpose oriented). Moreover, they have the most impact on the field[1].

Rasmussen's and Roudaut's Taxonomy

For clarity, we briefly describe the different features of Rasmussen's Types of Shape Change Taxonomy [43] and Roudaut's Shape Resolution Taxonomy [46]. Even though Roudaut *et al.* refer to Morphees as self-actuated flexible mobile devices, it is rather used within the community for the shape resolution features. As a consequence, we use the term Morphees for the taxonomy features. For the sake of simplicity, we mark *M* (Morphees) for Roudaut's taxonomy and *R* for Rasmussen's taxonomy.

Rasmussen's taxonomy

- *Orientation* (R.Orientation): distorts the shape through rotational or directional changes.
- *Form* (R.Form): changes the overall form of the shape while preserving the approximate volume.
- *Volume* (R.Volume): changes the overall volume of the shape while maintaining the approximate form.
- *Texture* (R.Texture): adds visual and tactile properties on the surface without affecting the overall form.
- *Viscosity* (R.Viscosity): makes the user perceive the surface as shifting between hard, soft, and vibrating.
- *Spatiality* (R.Spatiality): makes the illusion of shape change through a repositioning of element(s).
- *Adding/Subtracting* (R.Adding/Subtracting): unites or divides elements, while being able to return to the initial shape(s).
- *Permeability* (R.Permeability): alters the shape perforation, but able to return to its initial shape.

Roudaut's taxonomy

- *Area* (M.Area) is the surface area of the object computed as the area of the mesh convex hull.
- *Granularity* (M.Granularity) measures the density of physical actuation points.
- *Porosity* (M.Porosity) is the ratio of the Area of perforated parts to the total Area of the shape.
- *Curvature* (M.Curvature) describes the curviness of the surface, computed by removing π from the angle between 3 consecutive control points.
- *Amplitude* (M.Amplitude) describes the range of displacement of control points, computed as the distance between the rest position and the actuated position of a point on the surface.
- *Zero-Crossing* (M.Zero-Crossing) is the number of sign-changes between a pair of consecutive angles across the surface (capability of a shape to have wave-like forms).
- *Closure* (M.Closure) describes how "closed" a shape is, computed as $100 \times$ (Area - boundaries Area) where boundaries Area is the surface area of the shape created by using the control points situated on the edges.
- *Stretchability* (M.Stretchability) describes how much the surface distorts between two control points.
- *Strength* (M.Strength) is the force needed to move a control point from the minimum Amplitude position to the maximum Amplitude position of the shape.
- *Speed* (M.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.

[1] According to ACM digital library on June 15th, 2017, [43] and [46] are cited 82 and 52 times each. The other works were cited [4] 45, [35] 5, [26] 9, [44] 0, [56] 0 times.

Openable lamps (#18) change lamp shadows to change light quality

Blender (#36) can change the blades and containers according to the purpose.

Sword-canes (#52) are combined to conceal and walk, and detached to fight.

Tea pots and cups (#48) are combined to store, and detached to drink tea

Sand, Play-doh or Clay (#149) is molded to make 3D shapes.

Figure 2. Examples of collected everyday reconfigurable objects. The full collection of 82 objects with pictures is available at [24]. Photo credits (from left to right): the authors, Paul Goyette, Minnesota Historical Society, Counselling, Unsplash.

METHOD

We conducted a focus group to (1) collect daily reconfigurable objects, and (2) find design ideas for future reconfigurable interfaces. We then analyzed the collected objects and ideas based on Rasmussen's and Roudaut's taxonomies. In this paper, we only use the collected objects while the future interface ideas were kept for future research.

Collecting Deformable Objects

Nine participants (2 female; average age 22) were recruited on a university campus for the focus group. Participants had six different nationalities, with various cultures and customs in relation to different deformable objects (which indeed resulted in custom-related objects). They were also not experts in HCI, in order to avoid any researcher bias.

The focus group had two sessions, having a week interval. In the first session, a moderator explained types of everyday objects that the participants needed to collect. She asked to consider objects that are not only automatically and/or manually reconfigurable; but also objects that are not yet reconfigurable, but the participants wish them to be in the future. We deliberately kept the scope of objects wide to collect a variety of objects. She showed a few examples, e.g., a foldable ruler, sofa bed, etc., to help the participants understand reconfigurable objects. In addition, the moderator answered questions to ensure the instructions were clear.

During the week (7 days) between the two sessions, participants were asked to collect at least 15 pictures of reconfigurable objects from their everyday life. The participants could take pictures with their camera or get pictures from the Web. Some of them overlapped (e.g., Swiss army knife). They collected a total 96 pictures (examples in Figure 2). Note that some later examples are only referred to and not shown in pictures due to copyright.

In the second session, we aimed to gather further existing/future objects. The session lasted around 100 minutes and was divided into three activities.

(1) Welcome (20min): At the beginning of the session, two moderators provided hard copies of the pictures collected. A moderator explained the purpose of the focus group and facilitated their idea generation by introducing brainstorming rules and having a brief brainstorming game.

(2) First round (40min): participants were divided into two groups. Each participant chose one favorite picture among the pictures collected by the group. All participants were then asked to fill a sheet with (a) the picture; (b) deformation mechanisms in the picture; (c) purpose of the deformation; and (d) a title that shortly describes the object. Then, they explained the sheet to the group members. They were then asked to add further: (a) other objects with similar deformation; (b) other deformation mechanisms for the same object; and (c) other purposes for the same object. When they finished, they passed the sheet to the next participant and continued adding ideas to the initially collected objects. They repeated this procedure three times.

(3) Second round (30min): participants were given figures and features of deformations from previous works [43,46,52] to prompt ideation. Then the two groups swapped the sheets and pictures and continued the same activity as in the first round. After the second round, we had 149 deformation ideas, including the objects that were collected but not used during the focus group. As a consequence, 90min of focus group allowed us to add ~55% more ideas. The focus group enabled us to collect objects that we have not considered before (e.g., *#49 detachable bra straps*, *#133 kayak rudder*).

The researchers named and numbered the 149 objects separating the different parts of an object. For instance, *#22 bendable antenna* is counted as an idea different from *#23 telescopic radio antenna*, even though the two can be combined in a single object. Of 149 everyday objects, 82 were currently available to end-users. We reserved the other 67 objects for future research, which are natural objects (e.g., armadillo) or not existing yet (e.g., deformable fridge).

We present pictures of example objects in Figure 2 and full list in Figure 3, left column. The full collection of objects with their picture is accessible to the community [24].

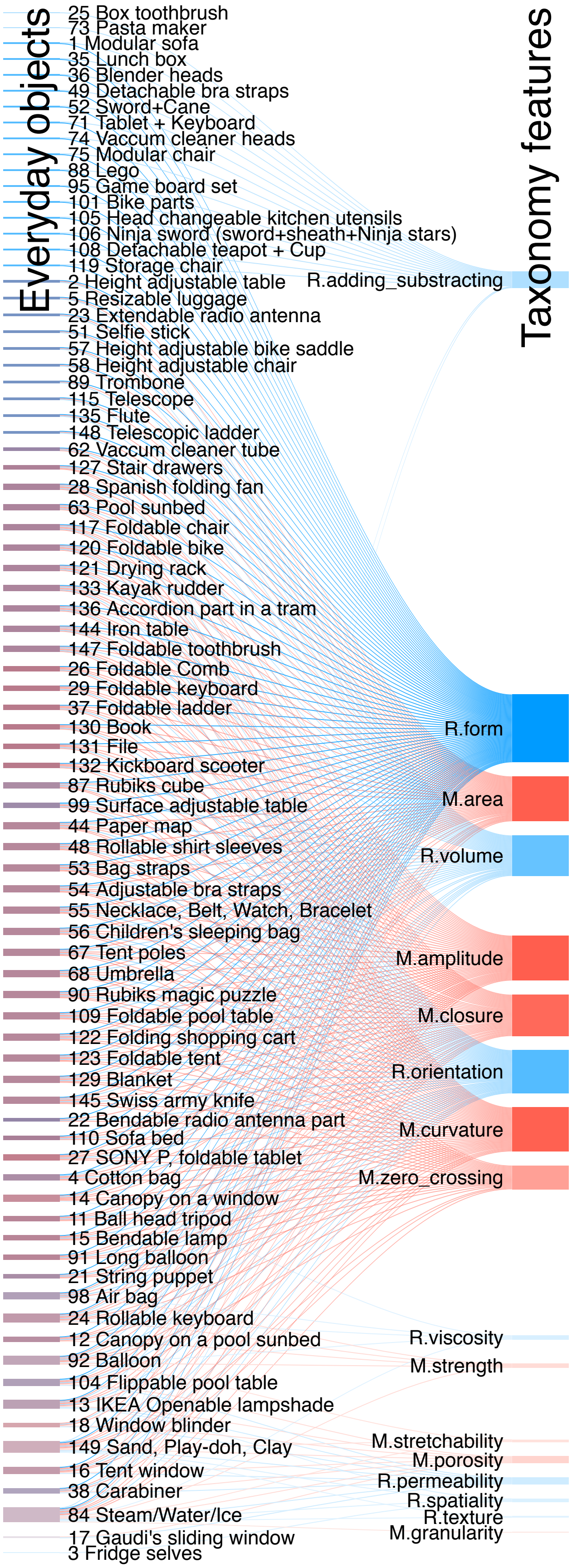

Figure 3. Everyday objects (left column) and the taxonomies' features (right column) they belong to. The thickness of each node shows how many connections it has. Rasmussen's features are blue, and Roudaut's features are red.

Object Analysis based on Topological Taxonomies

The three authors independently annotated the 82 deformable objects with Rasmussen's and Roudaut's 18 taxonomy features [43,46] on a separate spreadsheet. Note that we applied Rasmussen's taxonomy mostly on manual shape change, i.e., outside its intended area of actuated shape change. This was straightforward as its features are focusing on geometrical aspects regardless of actuation. For each object, we gave a binary value indicating if it has each feature of the taxonomies or not. The features were not exclusive; an object could have several features. Each author added notes to help future discussions if necessary. This work resulted in an average Pearson correlation between raters [8,9] of 0.319, indicating the annotation *subjective*. The ambiguity of the taxonomies led discussion until a consensus was reached (average Pearson correlation = 0.995). We discussed the disagreed features of each object. We iterated the discussion over all 82 objects around three times to keep the consistency for all objects. The discussion took more than 3 hours over two days.

Results

We visualized the agreed classification features of objects in Figure 3 and Figure 4. We used Google charts[2] and R[3] to create each figure.

Figure 3 shows a Sankey diagram with everyday objects (left column) and the taxonomies' features (right column). When an object has a feature, a link is drawn between them. The more links an object or feature has, the thicker its corresponding rectangular node. For instance, #84 Steam/Water/Ice (bottom third) has the thickest node among the objects, because it has the most features. Each column is vertically arranged to show their level of similarity: the more objects/features two items share, the closer they are. Rasmussen's features are blue, and Roudaut's features are red. The feature nodes' color intensities are relative to the number of links that they have. The objects have averaged colors of the linked features.

Figure 4 shows a heat map of the everyday objects classified by the features. The diagonal of the matrix shows how many objects were classified in each feature. On the upper-right triangle (equivalent to the lower-left triangle), we see how many objects the features share. As the color key and histogram on the right-side show, red-colored cell gathers the largest number of objects, and white cells gather very few objects (0 at least). The dendrogram on the left-side shows the clusters of similar features, at different levels of the tree. The length of each branch shows how different a cluster is from its neighbors.

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[2] https://developers.google.com/chart

[3] https://www.r-project.org/

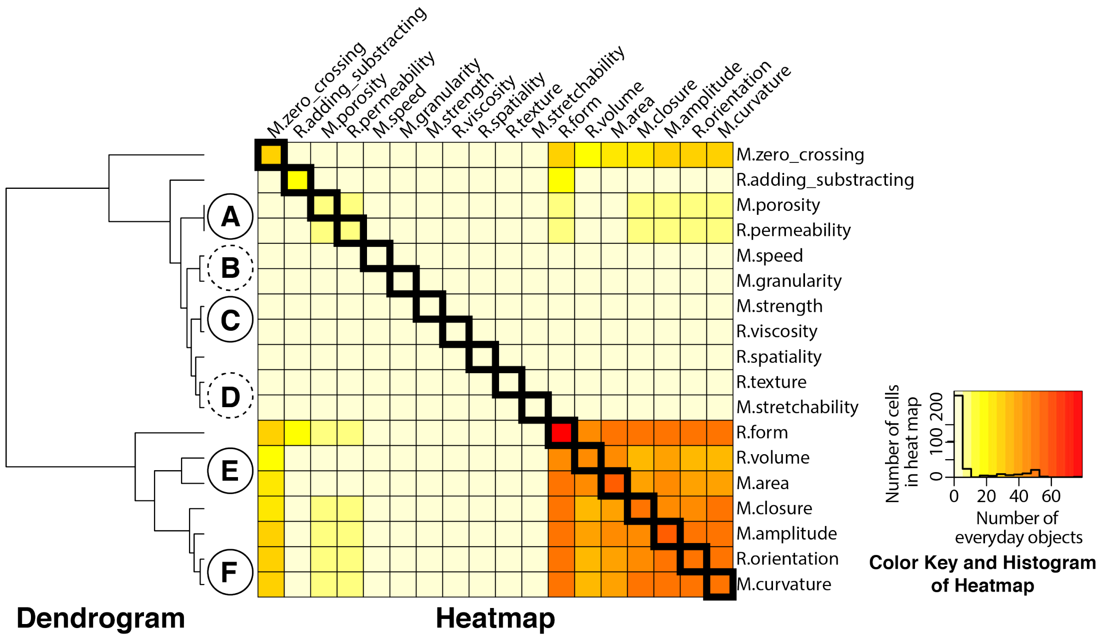

Figure 4. Number of objects that taxonomy features share. (Heatmap) The diagonal shows how many objects are in each feature; The upper-right triangle (equivalent to the lower-left) shows how many objects the features share. (Dendrogram) Clusters of similar features at different levels of the tree; The shorter length of branch (A) means the two features are more similar than the other clusters are (B-F).

These two figures, together with the notes during the annotation and discussion process, reveal three key findings: 1) the two taxonomies' underlying inconsistency and incompatibility; 2) suggestion to strengthen Roudaut's taxonomy; and 3) the relation between the features and object design and material.

ANALYSIS OF CURRENT TAXONOMIES

From the results, we gathered insights to improve the used taxonomies. We draw insights on homogenization between the taxonomies, and completeness and level of granularity of the features. We also discuss the level of precision in the definition of the features, which is the most important issue.

Homogenization between taxonomies

At the dendrogram in Figure 4 (left), some features overlap and form clusters from A to F at the leaf level. At cluster F, 49 of the 50 objects in M.Curvature also have the R.Orientation feature, and all the 49 objects that change R.Orientation also change M.Curvature. M.Porosity and R.Permeability (A) perfectly overlap with eight objects. Similarly, (C) four out of the five objects that change in M.Strength also change R.Viscosity, and vice-versa. Even though more data should confirm the overlap between the features, future homogenization of names would be beneficial for the research community.

The second interesting insight is related to the number of dimensions. Of the total 51 objects that have the 2D M.Area and of the 46 objects that have the 3D R.Volume feature, the vast majority (43) is shared between the two features. These two features also form a cluster (E) at the leaf level of the dendrogram, showing they are very similar. They tend to capture the same deformation while considering a different number of dimensions (surface vs. volume). E.g. a foldable chair (#117) increased its surface and volume when unfolded. One might ask then why the 1D extension transformation is not proposed in existing taxonomies.

The third interesting insight is the inclusion of some features in others. For instance, all 27 objects classified in M.zero-crossing also had M.Curvature. As a consequence, for all everyday deformable objects that we studied, it seems that a change in the number of zero crossing points implies the ability to change the curvature too. Positioning taxonomies and their features relative to each other would help the understanding of the design space further.

The number of objects that have M.speed, M.granularity, R.texture, and M.stretchability was too small (0, 1, 2, and 3 respectively) to consider their cluster B and D reliable (in dashed circles). Hence, we did not consider their correlation.

Completeness of the taxonomies

Everyday reconfigurable objects are all classified in Rasmussen's taxonomy. However, Roudaut's taxonomy, which focuses on the model of Non-Uniform Rational B-splines, does not consider attaching and detaching parts of the object. As a consequence, corresponding objects are not classified in Roudaut's taxonomy, although they are considered reconfigurable by the Rasmussen's taxonomy.

Granularity of features

Some features have many objects, while others few. Features with a large number of objects should be further detailed into sub-features in future work to precisely capture what is the deformation proposed to users. E.g. R.Form gathered almost all everyday objects, as we can see in Figure 4, the white cell in the heat map and Figure 3 is the thickest node (77/82 objects, i.e., 94 % of all objects).

Precision in the definition of features

When classifying, we found it difficult to attribute certain features to objects. In particular:

Ambiguous definitions

R.Orientation, R.Form and R.Spatiality leave room for subjective perception. It was difficult to classify an object objectively. R.Orientation is defined as "distorting the original shape through rotations or changes in direction while preserving the recognisability of the original form." We discussed whether we should agree to classify window blinds (#18) in R.Orientation. As they cannot bend, we chose not to classify them into it, even though users change the orientation of each layer.

R.Form is also lacking precision for us to easily classify many objects (defined as "transformations that preserve the approximate volume of the shape while changing its overall form"). We found that almost all deformable objects (77 of 82, corresponding to 94 %) change in form (white cell in Figure 4 and largest nodes in Figure 3).

R.Spatiality is also unclear for an object that can attach and detach, where spatial repositioning creates the illusion of shape-change if "individual elements being seen as part of a collective structure." During the discussion, it was difficult to objectively argue for detachable parts of the object being part of the whole.

It is unclear to compute R.Volume (defined as "changes in volume maintaining the approximate form"). We took the inspiration from M.Area, area of the envelope of the object, to compute R.Volume. We considered the envelope of the objects to compute both R.Volume and M.Area. For instance, a Spanish folding fan (#28) and rollable sleeves (#48) can be compacted to a smaller area and volume of their envelope, when they are folded. It thus means that we do not consider hidden surface and space, like inside of the radio antenna where concentric cylinders can be stacked. As a consequence, many objects we gathered changed M.Area (51 of 82, i.e., 62 %) and R.Volume (46 of 82, i.e., 56 %). An interesting possible future improvement would be to characterize how much change in M.Area and/or R.Volume contributes to the overall deformation, i.e., if this is a major or insignificant change.

M.Zero-Crossing is about the change in the number of zero-crossing points. So if a foldable object goes flat, then it can change from 0 zero-crossing points to N (fixed number) zero-crossing points. A future improvement can be to further define if a change in the number of zero-crossing points has to be greater than two (e.g., 0, N_1, N_2), to better distinguish it from M.Curvature.

Definitions that do not apply human perception

M.Amplitude is sometimes far away from the purpose of the object although they are easier to compute. For instance, a telescopic radio antenna (#23), by definition, changes its M.Area but not its M.Amplitude. However, it felt inappropriate to classify it this way as the purpose of the radio antenna is to change its height to better receive signals. After subsequent discussion, we decided that M.Amplitude was not considered when the extension of an object does not raise a single control point relatively to its neighbors on a surface. As a consequence, all telescopic objects (e.g., selfie stick #51 or extensible bike saddle #57) do not change in M.Amplitude.

Vagueness with modular objects

For M.Area and R.Volume, the difficulty comes from the object that is perceived as a single object and as several objects combined. For instance, the sword-cane (#52) did not have changing M.Area or R.Volume, where the Spanish folding fan (#28) had changing M.Area and R.Volume.

Similarly, **M.Closure is difficult to assess with modular objects**, like detachable bra straps (#49) or sword-cane (#52). We considered that they do not have M.Closure since the change does not happen on continuous surfaces. However, it needs further investigation since users may perceive the sheath is "closed" when the sword is in the cane, and "open" when the sword is out of the cane.

Shapes that have not been considered in previous literature

When objects have "openness," it is difficult to decide whether M.Porosity and R.Permeability are relevant or not. For instance, carabiner (#38) already has porosity, and we were not sure if its porosity changes. During the discussion, we concluded that its porosity changes because the central space becomes accessible from the side when it is open. We also considered they could show a change in M.Closure.

All raters agreed that **objects that can flip parts (like #104 Flippable pool table) were not easy to classify** because their deformation was not similar to the ones presented in previous papers. We decided to classify them in a change of M.Curvature and R.Orientation because the exterior skeleton and the central rotating part makes curved shape when it is being flipped.

In the case of **water that can change the state between gas (i.e., steam), liquid and solid (i.e., ice), it is difficult to assess the M.granularity**. In other words, it was hard to define what is a control point. One could say it is a molecule but we were not convinced it really makes sense in terms of user deformation. Similarly, it was difficult to decide if a liquid is stretchable because we struggled to define what are the control points.

MORPHEES TAXONOMY REFINEMENT

Our analysis showed several ways to improve current taxonomies. In this section, we propose refinement on Roudaut's Morphees taxonomy. We choose to start from Roudaut's one because the features, being mathematically defined, are more straightforward to apply compared to Rasmussen's one. Although one critique of Roudaut's one is that the features are sometimes far away from the purpose of the object, Roudaut's taxonomy offers a mathematical framework with rigorous metric. We think that the reliable classification through its precision is a good approach, and prefer to build on top of it. In the light of the issues revealed in our analysis, we propose to refine Roudaut's taxonomy by adding two new features (*Size* and *Modularity,* Figure 1) and refining one (*Granularity*). We also refine some of the metric definitions to accommodate our changes.

Adding a feature: *Size* (1D, 2D and 3D)

Size measures changes in the size of objects and can be split into 3 sub-categories that refine further the original definition of M.Area. We keep using imaginary envelopes of the objects (convex hull).

- *Length* (1D) is the length of the object computed as the length of the mesh in one dimension (cm).
- *Area* (2D) is the surface area of the object computed as the area of the mesh convex hull (cm^2).
- *Volume* (3D) is the volume of the object computed as the volume of the mesh convex hull (cm^3).

The sub-categories help the explanation of deformations and give more descriptive power to the taxonomy. Changes in each category would probably affect the other categories.

For instance, *Length* is good to describe actuated pin displays [11,14,53,29,31,33]. In inFORM [11], each pin can extend 100 mm. When all pins are fully extended, the interface volume increases approximately 14,516 cm^3. Examples for *Area* are foldable and rollable displays such as FoldMe [21] and Xpaaand [22]. Xpaaand reduces its *Volume* when reducing its *Area,* as the display is hidden in the boxes. When FoldMe has a folded shape, the *Volume* changes depending on the angles, but the summation of exposed surface area does not.

Some interfaces are better described in *Volume*, like pneumatic interfaces. For instance, the transformable tablet case [58], Inflatable Mouse [25] and morphing cube [17] change their volume to notify the user of the device status. Choosing a right sub-category would help designers precisely describe their complex reconfigurable devices.

Adding a feature: *Modularity*

Modularity is the ability of an object to be split into several parts (*n*) that can be combined while maintaining its original functionality. This feature essentially derives from the adding/subtracting feature of Rasmussen's taxonomy, which did not exist in Roudaut's original taxonomy. It is computed as the number of functionally possible combinations ($C_{possible}$) of *k* parts among *n* available parts in total (see formula below). Modularity is defined for objects that can be split into at least two parts (n>1).

$$\text{Modularity} = \sum_{k=1}^{k=n} C_{\ possible}(n,k), \text{ for } n \in \mathbb{N} \text{ and } n>1$$

For instance, the *Modularity* of the vacuum cleaner (#74) that can change between 3 suction heads H_1, H_2 and H_3 is 4, as it can combine its body B with all three heads (B, BH_1, BH_2, BH_3 are possible) where as H_1H_2, H_2H_3, H_1H_3, BH_1H_2, BH_2H_3, BH_1H_3, $H_1H_2H_3$ and $BH_1H_2H_3$ are not possible. Note that we also count B itself as it can serve the cleaning function. Another example is a set of cubelets[4]. Each cubelet has 5 faces that can be connected, 2 cubelets has 100 Modularity (= 5×5×4 = number of connecting faces of the first cubelet × number of connecting faces of second cubelet × number of possible connecting directions). An example from research is Topobo [40]. When there are two passive "straights," they have Modularity of 6. Objects that do not have pre-defined modules (#84 steam/water/ice and #149 Sand, Play-doh, Clay) have infinite modularity ∞.

As with Rasmussen's taxonomy of shape-changing devices, considering this type of reconfiguration of devices is inclusive and does not exclude many types of devices. We think this approach is appropriate given the high number of citations of Rasmussen's taxonomy[1].

Refining metrics (for modular objects)

With the addition of modular objects, we have to refine some mathematical definition of features. For the majority of features, it does not change their computation and can be considered as the sum of the feature values of each part. For instance, the *Curvature* of an object that can be split in two is the sum of the *Curvature* of each part. It works similarly for *Size, Amplitude* and *Stretching*. However, there are some changes to be applied in the features *Closure*, *Zero-Crossing* and *Porosity* of a modular object; one must first merge mesh of the possible combination of modules before computing these features. As a result, the space between modules becomes holes when modules are combined, thus increasing the value of *Porosity*. In a similar way, the value of *Closure* can now change even if the individual value of *Closure* for each module does not.

Refining control points

We ease the classification of features like *Granularity*, as it was hard to determine the number of control points of a deformable object. *Granularity* is defined as the ratio between the number of control points and the Area of the object. We now define as control points the joints or points that can control the change of shape of an object. In the case of the foldable toothbrush (#147), we consider only a single control point. Now a change in *Granularity* means that parts of the object can be grouped (removing a control point) and ungrouped (adding one). Liquid and fabric have an infinite number of control points. When a liquid is frozen, then it is grouped and its granularity lowers.

DISCUSSIONS ON IMPLEMENTING THE FEATURES

In addition to refining the taxonomy, we use the daily objects to analyze the different materials and physical links that allows implementing the reconfiguration features, in order to inspire future designs.

Based on Young's modulus [2], we first identified largely 3 types of materials: *elastic* (<~4 GPa), *stiff* (>11 GPa), and *hybrid* (consisting of both elastic and stiff materials). We classify the 82 objects according to the material types. There were 13 elastic, 54 stiff and 15 hybrid objects (examples in Figure 6).

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[4] http://www.modrobotics.com/cubelets/

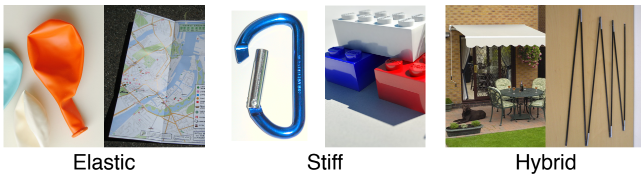

Figure 6. Example objects of *Elastic*, *Stiff* and *Hybrid* material. Elastic: #92 balloon, #44 map. Stiff: #38 carabiner, #88 Lego. Hybrid: #14 canopy on a window, #67 tent poles. Photo credits: Cookelma, Nikolaj, Polyparadigm, Max Pixel, Lilsarahp, chaoticandrandom.

In order to evaluate reconfiguration capability of each material type, we first count how many objects under a material type have a certain feature (a). For instance, out of 13 elastic objects, 11 objects have M.Area, and 13 objects have R.Orientation. We count the same for other material types. To eliminate the effect of the number of objects per material type, we divide this number (a) by the total number of objects in each material type (b). For instance, elastic objects that have M.Area is 0.846 (=11/13, Figure 5A), elastic objects with R.Orientation is 1 (=13/13, Figure 5B).

We then accumulate the relative numbers within materials types in Figure 5. We discuss the relations between material types and reconfiguration features using the number of objects per material type and relative numbers (color entities) in the figure.

Elastic vs. Stiff materials

From the number of objects in material categories, we see that stiff material objects are most common (54 out of 82 objects). The more exposure to stiff objects' deformation may cause more design ideas on mechanical deformations than organic ones as shown in an explorative design study [44]. It is also possible that users better perceive deformations of stiff objects, but this is not explored in this study.

Even though there are more stiff objects (54/82), they offer fewer deformation capabilities than other material type objects. Figure 5 shows that stiff objects support fewer features, e.g., they do not have M.Granularity or M.Stretchability. Stiff objects have fewer numbers of reconfiguration features on average; all color entities except R.Adding/Subtracting (second from the last) are smaller than the ones of elastic and hybrid objects.

Contrarily, elastic objects (13/82) have the most features (17 out of 18), because of the materials' intrinsic malleability. Most of them also had the possibility to change M.Granularity, with the notable exception of the ice state of water. Designers can try elastic materials when they need more reconfiguration features on one device.

Hybrid, between elastic and stiff materials

Not surprisingly, hybrid objects had higher relative numbers of deformation features than stiff objects, and less than elastic objects (Figure 5, bottom bar). It is generally because their elastic parts offer elastic materials' features, while stiff parts hinder the deformation. For instance,

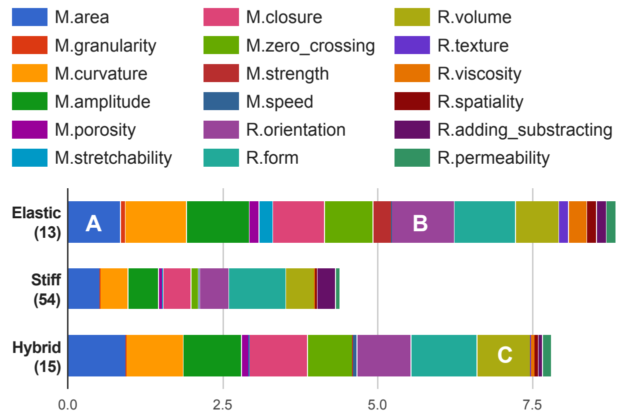

Figure 5. Relative numbers of objects with a certain reconfigurable feature. Counted and accumulated within each material type.

foldable tent (#123) has high deformability before it is set up. The stiff tent poles define its shape and limit its deformation on purpose.

Stiff parts in hybrid objects help quickly and largely deform elastic parts, and keep the shape (e.g., #14 canopy on a window). Examples from the literature are Obake [6] and morphing cube [17]. Similarly, when hybrid objects are wearable, elastic parts are used for a large surface that touches skin, and stiff parts are used to fix the size (#54 Adjustable bra straps). It contributes to more changes in R.Volume (C in Figure 5) than stiff and elastic objects (same color in middle and top bars). Elastic parts are sometimes used to control stiff parts jointly with gravity (#18 window blinds, BMW kinetic sculpture [60]).

Large capability of elastic materials

There are several features that only elastic objects have. Inflating stretchable material or changing hardness can change M.Stretchability. For instance, balloons (#92) get less elastic after inflation, and (b) clay (#149) gets hard and not stretchable after dry.

When designers aim to change M.Strength and R.Viscosity of elastic objects, they can (1) roll them multiple times (#24 rollable keyboard), (2) inflate (#98 air bag), or (3) change state (#84 steam/water/ice). The steam/water/ice and sand, play-doh, clay are the only objects that could change R.Texture by changing their status. Interestingly, previous works used methods such as using magnetic fluid [19], air pressure [10], and shape memory alloys [34]. Our work shows new mechanisms (1 and 3) to implement M.Strength and R.Viscosity.

Elastic materials can also limit the shape of objects. For instance, when the fan (#28) is unfolded, the covering fabric sets the maximum arc length. Another example is paper: although it is elastic, it better folds along a crease (#44 map). This allows fast prototyping of guided deformation as in Foldio [36].

Guided deformation with stiff materials

Deformation through lower pairs

Objects made of stiff materials have a fixed number of control points and deform only in pre-designed ways. It helps users learn the deformation by visual and force feedback. All stiff objects were classified in *lower pair*, a type of kinematic pair that constrains movement of a moving body to a matching fixed body through contact between their surfaces [45,49]. Figure 7 shows examples of lower pairs: *Revolute* (23 out of 54 stiff objects), *Prismatic* (16/54), *Screw* (0/54), *Cylindrical* (12/54), *Spherical* (2/54) and *Planar* (1/54).

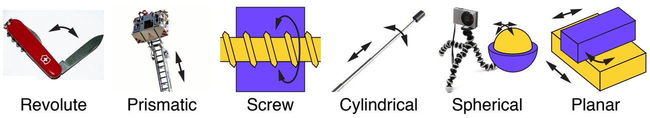

Figure 7. Examples of stiff objects and lower pairs [49]. From left to right: #145 Swiss army knife, #148 telescopic ladder, a screw pair, #23 telescopic radio antenna, #11 tripod, #1 modular sofa. Photo credits: Andy Rennie, markus53, SparkFun Electronics, Evan-amos.

The revolute, prismatic and screw pairs have 1 degree of freedom (DOF). Revolute (e.g., #145 Swiss army knife) and screw pair have a rotation, and prismatic pair has a translation. The cylindrical and spherical pairs have 2 DOF; i.e. 1 rotation and 1 translation for the cylindrical pair (#23 telescopic antenna), 3 rotations for the spherical pair (#11 tripod). The planar pair has 1 rotation and 2 translations (3 DOF), like an object freely lying on a table. Two pieces of the modular sofa (#1) technically makes the planar pair, but users use only one translation in real life as they do not lift up the sofa.

There was no object with screw pair. We assume that screw pairs are usually used to assemble parts for semi-permanent purposes (e.g., assembling a chair), not for deformation.

Implementing taxonomy features

Of 19 objects that have the R.Adding/Subtracting, 16 are stiff objects, and they have only prismatic or cylindrical pair (e.g., #23 bike saddle). We assume that the pairs' linear freedom eases the recombination, although it often needs additional systems (e.g., bike saddle clamp) to retain the combination.

The limited deformations of stiff materials can be overcome through careful mechanical designs. For instance, an openable lamp (#13, Figure 2 left) uses the same revolute pair as pool sunbed (#63), but it has 3 more features (R.Permeability, R.Spatiality, M.Porosity). On the contrary, a design can reduce a pair's degree of freedom. For instance, a Lego block's (#88) stud has a cylindrical pair, but the multiple studs on a block allow only a vertical translation.

Additionally, we found an additional method to implement M.Porosity and R.Permeability other than the revolute pair that was used in Shutters [5]; a ventilation window (#17) can open holes through a prismatic pair (sliding).

LIMITATIONS AND FUTURE WORK

A limitation of this work is the lack of exhaustive coverage of everyday objects. To improve this, the collection of daily reconfigurable objects is now open for contribution [24]. Another limitation of the work is the classification's subjectivity. To address this problem, the general public could be engaged in the classification through gamification.

Another limitation is that we do not know if some features are underused because of technical limitations or because end users do not perceive them well. Future research should reveal the difference between an actual change in shape and its perception by users [18].

Most objects we collected are manually deformable and thus only inform us on shapes at a state, and not how they transit between states. Features like M.Speed thus seems orthogonal to the others. Rasmussen's taxonomy treats this feature separately, alongside other kinetic parameters. Further investigation is needed to investigate these kinetic features.

Future work will collect reconfigurations inspired by nature. Example of these are armadillos who roll up into a ball when threatened by a predator and Venus flytraps that snap shut when insect crawl on their leaves. Studying their mechanisms can reveal new, miniaturized, and sustainable shape change mechanisms.

An important next step is to evaluate the refined Roudaut's taxonomy, to ensure that the improvements presented here also benefit research. As a form of evaluation, we plan to verify that the refined taxonomy can describe existing interfaces and inspire new ones.

CONCLUSION

Ad-hoc considering of existing reconfigurable objects has enabled researchers to use their affordance as well as quickly evaluate interactions with low-cost prototypes. This paper presents the first systematic study of reconfigurable everyday objects. We present a collection and analysis of 82 reconfigurable everyday objects to inform the design of reconfigurable interfaces. We revealed the similarity between two representative shape-changing interface taxonomies and areas for improvements, such as their subjective comprehension. We refined Roudaut's taxonomy by adding the Modularity and Size, and adjusting the other features. By looking at the materials of the objects, we provided a better understanding of how to implement the reconfiguration features. We hope this work generates new research directions by revisiting existing objects and broadening the research area of reconfigurable interfaces.

ACKNOWLEDGEMENT

This work was supported by the Leverhulme Trust, the French National Research Agency (ANR-11-LABX-0025-01, ANR-15-CE23-0011-01), the Alexander von Humboldt Foundation, EPSRC (EP/P004342/1), and the German Federal Ministry of Education and Research (Be-greifen 16SV7527). We would like to thank the participants of the study, and our colleagues and reviewers for their feedback.

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