EXHI-bit: a Mechanical Structure for Prototyping EXpandable Handheld Interfaces

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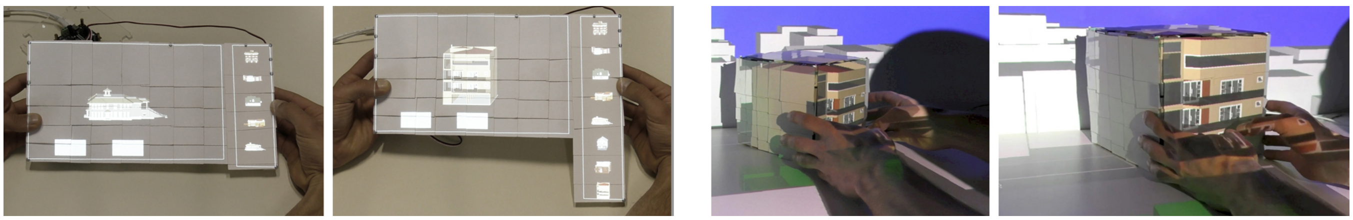

Figure 1: Shape-changing interfaces made with EXHI-bit surfaces. *left*: A right-angled interactive surface prototype. *right*: A volume prototype.

ABSTRACT

We present EXHI-bit, a mechanical structure for prototyping unique shape-changing interfaces that can be easily built in a fabrication laboratory. EXHI-bit surfaces consist of interweaving units that slide in two dimensions. This assembly enables the creation of unique expandable handheld surfaces with continuous transitions while maintaining the surface flat, rigid, and non-porous. EXHI-bit surfaces can be combined to create 2D and 3D multi-surface objects. In this paper, we demonstrate the versatility and generality of EXHI-bit with user-deformed and self-actuated 1D, 2D, and 3D prototypes employed in an architectural urban planning scenario. We also present vision on the use of expandable tablets in our everyday life from 10 users after having interacted with an EXHI-bit tablet.

CCS CONCEPTS

• **Human-centered computing** → User interface toolkits;

KEYWORDS

Shape-Changing Interface, Organic User Interface, Expansion, Handheld device, Tangible User Interfaces

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1 INTRODUCTION

Almost a decade ago, research in tangible user interfaces started to take advantage of shape changes for embodiment and interaction with dynamic digital information ([19, 22], *resp.*). Since then, several studies explored *Organic User Interfaces* (*OUI*) [8], and more recently *Shape-Changing Interfaces (SCI)* [1]. This research axis is active enough to provide surveys (e.g. [1, 26]), exploratory studies on user experience and perception (e.g. [14, 17, 20]), and models that describe and explore the design space of such interfaces [1, 17, 26, 29, 36]. However, in spite of this work demonstrating the great potential of *SCI* in interaction, the technology does not yet exist for providing all of the features (i.e. types of changes) described in the *SCI* literature.

As design concepts, *Expansion* is described in the *SCI* literature under the names of *Area* (e.g [29]), *Tapering* (e.g. [6]), and *Volume* (e.g. [36]). From a user experience point of view, a recent study from Pedersen et al. [20], that uses videos only, shows that expansion has received very positive feedback from users. For instance some users intuitively interpreted the 2D expansion as a practical feature that allows the device to function both as a smartphone and as a tablet. From a technical point of view, the expansion feature is essential for making generic objects, able to adapt their shape to the context of use. Jansen et al. [10] demonstrated the benefits of "physical visualization", highlighting features that are unique to physical objects. However, even though digital fabrication makes physical objects increasingly easy to build, it will always be limited by the production time and the waste of matter it generates. This is a crucial issue for visualization since data often change, thus one has to often re-build the physical object. An expandable object, able to take the correct shape AND the correct scale for displaying data would be a faster and more ecological solution. Beyond "physical visualization", the same principle applies to any interaction task that uses multiple tools or props. Indeed, instead of using several tools for performing the task, it could be more efficient to use a single tool that adapts itself, i.e its shape, to each task. This could decrease the homing time (if the expansion transition is fast enough), it is less cumbersome, and it guarantees to always have the useful tool right at the users' fingertips.

To go further in the exploration of the great potential of expansion for interaction (i.e in the users' hands), prototyping tools are now necessary. To overcome this limitation, we present a new mechanical structure, EXHI-bit, for prototyping expandable handheld interfaces. EXHI-bit enables prototyping of unique shape-changing interfaces in order to investigate the interaction potential of expansion. In particular, EXHI-bit defines an "expandable surface" that continuously expands in two dimensions, while maintaining both rigidity and zero porosity. Such surfaces can be combined for making 2D and 3D multi-surface objects that can be handheld as well.

In this paper we first present the requirements for a generic structure that enables expandable handheld interfaces and we sample key related work according to these requirements. We then describe (1) the EXHI-bit mechanical structure, (2) a decision support scenario, and (3) an interview of 10 users after having interacted with an expandable tablet.

We present the following main contributions:

- EXHI-bit, a mechanical structure, for prototyping EXpandable Handheld Interfaces, actuated by the user or the system, enabling interfaces that expand in 1, 2, or 3 dimensions.
- Unique 1D, 2D, and 3D prototypes for linear, surface and volume expansion (one, two, and three dimensions resp.), that demonstrate the versatility and generality of EXHI-bit.
- Vision on the use of expandable tablets in everyday life from 10 users.

2 REQUIREMENTS

For prototyping expandable handheld interfaces, we investigate mechanical structures that enable us to make handheld interfaces that expand in 1, 2, or 3 dimensions. Besides the handheld aspect and the expansion dimensions, we identify three key requirements for creating a generic structure: the rigidity of the surface, the porosity of the surface, and the continuity in transitions.

Rigidity is the interface ability to maintain its rigid shape before, during and after the expansion/retraction movement. Maintaining rigidity is essential for comfort and efficiency during handheld interaction. For example, with a tablet most people use the dominant hand to interact, and the non-dominant hand to support the device. Wagner et al. indeed proposed bi-manual interaction [35] and demonstrated its efficiency. However, this is only possible because the tablets are rigid enough. If a tablet would be as flexible as a sheet of paper, this would force the user to adopt specific postures for interaction, e.g. laying the device on the forearm, or pinching the bottom of the device in order to slightly fold it and improve its rigidity. Both positions drastically limit interaction by decreasing comfort and efficiency when pointing and dragging on the surface. Hence, for handheld interaction, an expandable interface should be rigid enough at any expansion state.

Porosity [29] is the discontinuity in a surface, e.g. holes or perforated spaces, before, during and after the expansion/retraction movement. A non-porous surface is essential for maintaining interactional consistency for both output and input. For output, by increasing the surface area, one could expect to increase the display area in order to display more information. If expanding the shape implies expanding holes instead of expanding the display area, then no visual benefits will be provided. For tactile input, it is even more critical as the interaction would be disturbed each time the finger falls into a surface's hole.

Continuity in transitions is the interface ability to provide any intermediate expansion state between its two extreme states: the fully retracted and fully expanded states. First, continuity is essential for providing a great number of shapes and sizes defined in between the two extreme states. Second, continuity allows fine tuning of the shape and of the size. Indeed, considering expansion in two or three dimensions, continuity allows us to not only change the global scale of an interface, but also its shape. For example, a rectangular surface can expand to a trapezoid. Finally, continuity minimizes the cognitive load during the transition [27]. Indeed, with continuous transitions the users can track the content modifications (i.e they never loose the context) and can interact during the transitions.

3 RELATED WORK

The current *OUI* and *SCI* literature classifies the shape-changing interfaces according to the features they provide, e.g. in [26]: orientation, form, volume (3D expansion), texture, spatiality, etc. We focus on the expansion feature only. In light of our requirements (i.e. rigidity, porosity, continuity in transitions, handheld device), we review existing research according to the expansion dimensions.

3.0.1 Expansion in 1D. Khalilbeigi et al. presented the device concept *Xpaaand* [12]. The described prototype is a rollable display, whose size is controlled by the user. Several benefits result from physical resizing and the principle has been updated by Steimle et al. to support collaborative interaction [32]. Such a surface is non-porous, and provides continuous transitions. However, these approaches are limited to expansion in one dimension only. Moreover, the rigidity is too low and the material is too flexible to stand on its own for handheld usage.

Instead of rollable displays, another approach consists of folding displays as Hinckley et al.'s *Codex* [7], Khalilbeigi et al.'s *FoldMe* [11], and more recently Gomes et al.'s *PaperFold* [4]. *PaperFold* is a notebook that folds over itself, and then changes to a tablet and a smartphone, using three hinged/detachable screens. According to the task, the user can have a one, two, or three display-size device. This system proposes a high expansion ratio, with no porosity. However, the number of possible sizes is very limited and predefined, making the transitions discontinuous: the device changes from one size to another without intermediate positions. The system can be handheld, but it is not rigid enough to stand on its own.

3.0.2 Expansion in 2D. Ramakers et al. also proposed a folding approach for making expandable displays: *Paddle* [24]. In this approach, the display can be folded and unfolded in two directions, providing thus predefined display sizes. Even though it provides 2D expansion, this approach has the same limitations as *PaperFold*. Another folding technique has been proposed by Takashima et al.: *TransformTable* [34], an interactive digital table, whose 2D shape and size can be physically and dynamically deformed. The table can increase its size and can transform from a square to a disc. Here again, even though the device is rigid and non-porous, there is no continuity in transitions. Moreover, it is not a handheld system. Combining flat displays is another approach that has been investigated by Girouard et al. in *DisplayStacks* [3]. The system dynamically tracks the position and orientation of a flexible display when the latter is stacked on another. The system uses the entire display surface (that can consist of many displays) for visual feedback and interaction. Transitions in expansion are continuous. However, the displays are not attached so the whole system is hard to hold as soon as there are more than two displays. On expansion dimensions, expanding in one dimension make a consistent large display, i.e two displays become one. In contrast, expanding in two dimensions, i.e moving the screens diagonally, makes specific shapes. This causes the user to perceive an assembly of displays more than a consistent single large display. Indeed, expansion of two stacked screens diagonally makes large holes in two opposite corners. Thus, the system does not fulfill the non-porous requirement. Nevertheless, overlapping flat surfaces is an interesting principle that we reuse in our new structure (see following section). Roudaut et al.'s *Changibles* [30] use scissor jacks for moving a flat face of an object. Shape expansion is further studied by assembling elementary objects, as in [18, 23]. Transitions are continuous, and the authors started working on porosity by using Origami, i.e Miura structures. However, the assembly system is likely not rigid enough to be handheld, the expansion is provided by the border elements only, limiting the expansion ratio, and Origami does not provide flat surfaces during expansion.

Hemmert et al. proposed to control the shape of a mobile phone by using two-dimensional tapering [6]: the back plate of the phone is actuated via two scissor jacks as in *Changibles*. Here, the handheld device is rigid, non-porous, and transitions are continuous. The range of possible shapes is then high, but the expansion is small and only made for haptic information to the user (i.e. outputs only). Focusing on inputs and outputs, Rasmussen et al.'s *ReFlex* mobile phone prototype [25] includes four servomotors at each corner of a phone prototype. *ReFlex* provides 2D independent expansions of both the left and the right backside, with continuous transitions. Compared to Hemmert et al's prototype [6], the number of possible shapes is higher, but the global shape still does not significantly change and expansion is small.

3.0.3 Expansion in 2.5D. Poupyrev et al. have been one of the first to investigate shape-changing surfaces with *Lumen* [21]: a tabletop system that consists of a two-dimensional array of movable light guides. Their heights and colors can be individually controlled to create images, shapes, and physical motions. This approach has been updated by Follmer et al. to provide a faster system with higher resolution: *inForm* [2]. To improve the expressivity of interaction with table-sized shape-changing surfaces, Sahoo et al. used an elastic fabric surface instead of pin-actuators with *TableHop* [31]. As shown by the authors, the vertical expansion of this kind of shape-changing displays defines a large space of interaction possibilities. The displays are rigid enough for interaction, define non-porous surfaces, and support continuous transitions. They are however expensive large systems that cannot be hand held. For handheld interaction, *Emergeables* [28] implement a similar approach. *Emergeables* are mobile surfaces that can deform to provide fully-actuated tangible controls. Nevertheless all these prototypes expand the vertical dimension only, so they can simulate 2.5D shapes only, e.g. they cannot simulate objects with negative slope angles. Finally, the "horizontal"

System	*Rig*	*NPor*	*CTrans*	*HHeld*	*Dim*
Xpaaand [12]		+	+	˜	1D
Ha. tabletop [32]		+	+	˜	1D
Codex [7]	+	+		+	1D
FoldMe [11]		+		+	1D
PaperFold [4]		+		+	1D
Paddle [24]	+	+		+	2D
Trans. Table [34]	+	+			2D
DisplayStacks [3]			+	˜	2D
Changibles [30]		˜	+		2D
SC Mobiles [6]	+	+	+	+	2D
ReFlex [25]	+	+	+	+	2x2D
Lumen [21]	+	+	+		2.5D
InForm [2]	+	+	+		2.5D
TableHop [31]	+	+	+		2.5D
Emergeables [28]	+	+	+	+	2.5D
Volflex [9]	+	+	+	+	3D dep.
Inf. Mouse [13]	+	+	+		3D dep.
Inf. display [33]	+	+	+		3D dep.
PneuUI [37]	+	+	+	+	3D dep.
EXHI-Bit	+	+	+	+	1/2/3D

Table 1: Requirements and existing studies on expansion. *Rig*: rigidity, *NPor*: none porosity, *CTrans*: continuous transitions, *HHeld*: handheld device and *Dim*: the number of dimensions in expansion. '+': the approach fulfills the requirement. '˜': the approach partially fulfills the requirement. 'dep.': dependent dimensions.

dimensions can be exploited by combining several devices, but this is an involved process.

3.0.4 Expansion in 3D. Pneumatic actuation has been used to make 3D deformable devices. The haptic volumetric display *Volflex* by Iwata et al. [9] is made of a set of air balloons controlled by air cylinders. This display provides a surface as clay offering input and output feedback. Kim et al. proposed *Inflatable Mouse* [13]. The volume of the mouse is adjusted with air-pressure. Stevenson et al. defined an inflatable display [33] that can deform from a flat circular display to a hemispherical display. The 3D deformable display is illustrated with earth data. Here, the devices rigidity seem sufficient for the task, the transitions are continuous, and the shape is non-porous. However, air-pressure is one dimensional: thus only the volume "scale" can be controlled. Indeed, the three dimensions of the expansion are controlled in a combined and simultaneous way. The global shape is predefined, or cannot be fine tuned. The same remarks can be applied to the work of Yao et al.: *PneUI* [37].

Table 1 summarizes our review of existing research according to our requirements. Our literature search did not reveal expandable handheld interfaces that expand in three independent dimensions, while providing rigidity, non-porosity, and continuous transitions. The following section describes EXHI-bit, the new structure we propose for making such interfaces.

4 EXHI-BIT

The EXHI-Bit principle derives from 3D modeling, where 3D models are defined by surfaces made of triangular or rectangular faces. In the same way, we adopt a composite approach (as opposed to a monolithic one as in [33] for instance) in which the elementary building block is an expandable face made of EXHI-Bit units (Figure 2). This enables us to design UIs on the continuum between"thing" and "stuff" as in [15].

4.1 Unit

For making an EXHI-Bit unit, we first investigated soft materials (e.g. fabric or printed flexible plastic) with included small telescopic structures. The resulting prototypes were not rigid enough and the manufacturing was long and hardly reproducible. We also considered the scissor-jack principle, proposed by [6, 30]. The increase of complexity of the resulting prototypes was directly related to the number of expansion dimensions. Again it led us to not sufficiently rigid and more complicated structures. Finally, we investigated a mechanical structure with sliding parts, made of plastic that any fablab possesses and can lasercut.

Thus, an EXHI-bit unit is made of stacked layers (Figure 2). Five plastic layers (from 2 to 6) support the expansion mechanism. Two of them (3 and 5, i.e the blue layers) are the interweaving parts that make the unit slide away from its neighboring units. These two layers are separated by a thin disk of plastic (4) for providing smooth sliding and avoiding of interlocking. Two other layers (2 and 6) sandwich the interweaving parts in order to hold them together, but also for keeping them connected with the outgoing parts of the neighboring units. This is essential for making a self-supporting structure. A set screw (7), passing through the central hole of the layers, tightens the unit. However, the hole of each layer is large enough to avoid screw hanging, except at the top layer (2) in which the screw is blocked. The interweaving parts can then freely rotate around the axis made by the screw. With these layers only, about 10mm thick, an EXHI-bit grid is expandable and rigid, but still porous. The top layer (1) ensures the zero porosity of the surface. It is a "*as thin as possible*" layer, and we call it a tile (like the overlapping tiles of a house's roof). Tiles are firmly pasted on top of each unit (on layer 2), matching one corner and two edges. The size of a tile has to abide by two constraints:

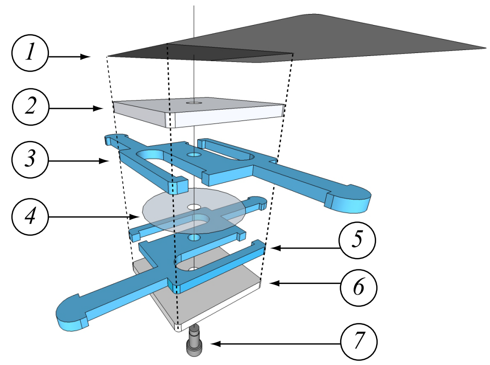

Figure 2: Layers for a 2D expansion unit. *1*: Paper tile (44x44mm, 200g) whose darker part is pasted onto layer *2*. *2* & *6*: Plexiglass squares (24x24mm, 3mm thick plexiglass). *3,5*: Interweaving parts (2mm thick plexiglass). *4*: Thin plastic disk for improving sliding of interweaving parts and for avoiding interlocking (22mm diameter). *7*: Screw, that only screws in layer *2* (*2* has a smaller central hole than the others), making a rotation axis for layers *3, 4, 5, 6*. The unit is about 10mm thick.

(1) When the surface expands, i.e the units move away from each other, the tile should hide the gaps. Also, for providing a smooth sliding of the surface, and to avoid interlocking, the tiles have to always maintain their initial overlapping sequence. Hence, for these two reasons a tile has to be **strictly larger** than the sum of two values (Figure 3): the size of one unit (u) and the size of the gap between two neighboring units (g).
(2) For ensuring a surface to have consistent edges in any expansion configuration, and also to be combined with another surface (i.e both have a common edge), tiles have to be **slightly smaller** than twice the size of one unit in each dimension. Indeed, as shown in Figure 5, some units can be rotated with respect to the others in order to make trapezoidal faces. For this case, too large tiles could then protrude too much from the shape border, making undesirable final shapes.

In our prototype we use projection for displaying on the surface. The tiles are then made of paper (200g). In future

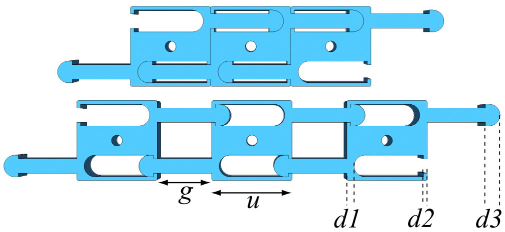

Figure 3: One dimensional grid of three units. *top*: Fully retracted. *bottom*: Fully expanded. *u* is the size of one unit. *g* is the size of the maximum gap between two units. *g = u - (d1 + d2 + d3)*.

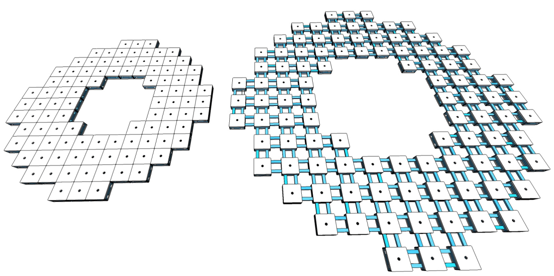

Figure 4: Example of a none rectangular EXHI-bit structure: fully retracted and fully expanded circle with a central hole (tiles are not displayed). Units from internal and external borders are slightly different, i.e two *fingers* of their interweaving parts are missing.

improvements, we envision EXHI-bit being made of thin and flat displays for each tile.

EXHI-bit units can be combined into a linear (1D) configuration (Figure 3). In this particular case, only one interweaving layer (3 or 5) is used, and no plastic disk (layer 4). The constraints for the tiles are then applied in one dimension only. The characteristics of a single unit we use in our prototypes described in the following section are: $u = 24mm$ & $g = 16mm$. In these, the maximum expansion ratio (i.e ratio between the fully retracted configuration and the fully expanded one) is 166,66% per dimension. A method for calculating the expansion ratio is provided in the accompanying files along with the models for the EXHI-bit structure.

4.2 Surfaces

An EXHI-bit surface is a grid of nested units. Each unit slides from each of its direct neighbors (none diagonal), making the grid expandable along two dimensions independently. The grid is not necessarily a rectangle or a square. A parallel can be made with pixels (the units) that fill a 2D polygon (the surface): the EXHI-bit assembly *fills* the surface in a discrete way, with a resolution dictated by the size of one unit. For a given surface, the smaller the size of a unit, the higher the resolution will be. The resolution has an impact on the surface's edges: as for pixel resolution, the resolution

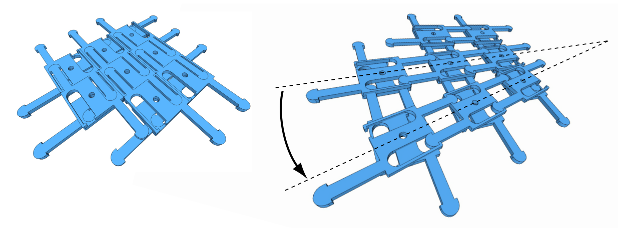

Figure 5: Behavior of a two dimensional grid (interweaving layers only). As two interweaving layers of the same unit can rotate around a common axis, two rows are not forced to stay parallel.

must be such that the edges do not appear serrated. This is particularly important for any expansion configuration that is not a rectangle or a square, e.g trapezoids or surfaces with holes like the one of Figure 4. Moreover this is critical in order to be able to combine surfaces that share edges as for 3D prototypes (see section Multisurfaces and Volumes below).

Figure 5 shows the behavior of the interweaving layers when expanded into a trapezoid. The trapezoid dimensions are of course limited by the expansion ratio in each dimension. With a unit (Figure 2) of u = 24mm & g = 16mm, a surface prototype made of 5x7 (as the prototype 1 of the application scenario - Figure 8) have an expansion ratio of 241% (see the accompanying files for the calculation of the expanded ratio).

In theory, the number of units in each dimension is not limited. In practice, the size of the surface is limited by the rigidity of the mechanical units (thickness and hardness of the material). In our prototypes we use plexiglass (2mm thick). The size of the largest prototypes we built are 26.4 cm width by 18.4 cm height: for this size, 2mm thick plexiglass was perfect for the rigidity of the resulting handheld tablet.

4.3 Multisurfaces and volumes

Each EXHI-bit surface, made of EXHI-bit units, can continuously take all the shapes from the fully retracted configuration to the fully expanded one. However, combining such surfaces increases the shapes possibilities for 2D prototypes (Figure 1-*left* and 6-*left*). In the same way as for 3D modeling which consists of assembling triangular or rectangular faces for making a 3D volume, EXHI-bit surfaces can also be combined for making volumes (Figures 1-*right* and 6-*right*). For combining surfaces, two different ways enable us to link surfaces two by two. The first way consists of linking two adjacent surfaces with a common edge. Here, the expansion of the edge modifies the shapes of the two adjacent surfaces simultaneously. The edges can be actuated or not, and the main challenge then lies in finding the appropriate joint for connecting the edges' extremities (see the corner joints for the Volume prototype in Figure 7). Such a joint has to (1) be deformable enough to allow the surface expansions, and (2) be rigid enough to guaranty the self-supporting of the entire structure. Then, the force needed to deform this joint should be (1) lower than the force applied by a user or by

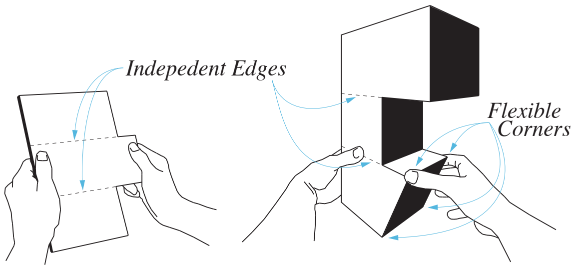

Figure 6: Two examples of EXHI-bit configurations. *left*: A tablet with three drawers. The user perceives a single device while it consists of three EXHI-Bit surfaces with *independent edges*. *right*: Same principle in 3D, with four drawers. This device combines the two ways of connecting EXHI-Bit surfaces: *Independent Edges* for connecting the drawers, and *Flexible Corners* for each drawer. This allows the drawers to take none rectangular shapes.

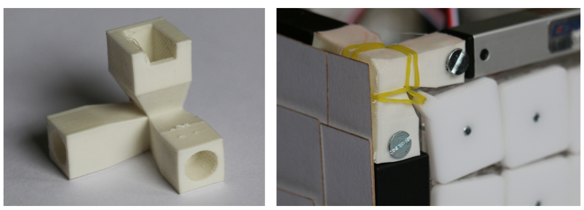

Figure 7: Flexible Corner (made of flexible Thermoplastic TPE) in the Volume prototype. They ensure the self-supporting of the frame at any expansion configuration. *right*: A slightly modified unit (layer *2*) enabling us to attach it to the corner joint with small elastic cords.

an actuator when expanding the structure, and (2) higher than the force applied by the structure itself when collapsing. The joint can then be mechanical, i.e assembly of rigid pieces that slide between each other, or flexible, i.e. a unique piece of deformable material. We choose the second solution for our Volume prototype (Figure 7), which derives from a cube. A 3D printable model of the corner is provided in the accompanying files. It can be easily adapted, i.e by changing the number of legs or the angle between them, for making other EXHI-bit prototypes like a sphere for instance (flatter corners with 4 legs). This principle can also be used for 2D: joining two faces with a common edge allows expansion from a rectangle to an hexagon.

The second way to combine surfaces consists of attaching the surfaces while keeping independent edges. Each attached edge can be actuated or not, but is free to expand. Thus, each surface can expand independently (Figures 1-*right* and 6). In the right-angled prototype of the following application scenario (Figures 1-*right* and 9), we pasted magnets on the static parts of the actuators, making a single device with a right-angled expansion, while allowing users to detach the surfaces if needed.

5 BUILDING EXHI-BIT PROTOTYPES

The EXHI-bit prototypes we built are all presented in the following application scenario. They are all based on the same single unit, i.e same mechanical structure and same specification: $u = 24mm$ & $g = 16mm$. Their layers are made of plexiglass ($2mm$ thick), and paper ($200g$), cut by a Trotec Speedy 300 laser cutter. For allowing the paper tiles to slide from each other without interlocking, they have to be pasted in a specific order: from one corner of the grid to the opposite corner, following rows in the same direction at all times. The non-pasted part of each tile is then (1) on top of the previously pasted tile, and (2) on top of the tiles of the previous row (see the accompanying video). The flexible corners (Figure 7), and the magnetic hinge between two EXHI-bit surfaces (Figure 9) are printed with a MakerBot Replicator.

The self-actuated prototypes are framed by actuators of two sizes: Firgelli L12_50_100_06_R and Firgelli L12_100_100_06_R, stroke length = $5cm$ and $10cm$ resp. These actuators keep their current expansion even when switched off, so that the prototypes can maintain their current expansion while the user holds it. The expansion speed is limited by the actuators' velocities: 23mm/s for the short ones, and 12mm/s for the long ones. The actuators are connected to an electronic board (Phidget 1061_1), that can control up to 8 RC servo motors. The board is connected to a power supply (12V), and to a computer via a USB connection. The actuators are attached to the structures with specific joints/corners (Figure 7). These joints have been designed for matching the actuators extremities. They are printed with a 3D printer, and made of flexible Thermoplastic TPE.

The applications use an optical tracking system (Natural Point system, with four Prime 13 cameras), connected to a computer (Apple MacBook Pro, IntelCore i7, 2.6Ghz with an Nvidia GeForce GT 650M). The tracking system has been used for tracking the prototypes, one fingertip (for the linear and surface expansion prototypes), and the user's head position (for the volume expansion prototype). As the prototypes have no fixed shapes, we cannot use rigid-body tracking. We independently track retroreflective markers (half spheres about $4mm$): one pasted on the fingertip, one on glasses without lenses worn by the user, and several on the prototypes. We track each prototype's faces independently, with the following principle. We paste four aligned markers on the main edge of each face: one on the edge's extremity, and three others on the other extremity (blue dots in Figure 9-*left*). The three markers are regularly spaced from the extremity, and these spaces are not affected by the edge expansion (all pasted on the same tile for example).
The first step of the tracking algorithm consists of identifying the face main edge of the face, by looking for the three-marker group of the face. Then, for each face, the fourth marker is easily linked with the first ones since it is aligned while the distance varies according to the expansion. Depending on the expansion dimensionality, i.e 1D or 2D, we paste one or two additional markers on respectively one or two other

corners. The tracking algorithm makes assumptions from the prototype characteristics (e.g. expansion dimensionality, minimum/maximum faces sizes, or faces adjacency) for associating these markers to their owning face and then reconstructing the current shape of each face of the prototype.

All the applications use a unique projector (Epson FullHD EH-TW3200, 1920x1080px) for displaying onto the EXHI-bit interfaces and around them, as in [16] for combining shape-changing interfaces and spatial augmented reality. Projecting on a multi-faceted object is now common (using basic OpenGL functionalities), especially on objects with well-determined facets. For each facet, one 3D rendering is computed (and not displayed) from the camera position through the face, and recorded on a texture. The texture is then displayed at its corresponding position onto the EXHI-bit interfaces.
The software has been developed from scratch in Python 2.7, using PyOpenGL, and PyCollada for importing models from 3D Warehouse [5].

6 APPLICATION SCENARIO

For demonstrating the versatility and generality of EXHI-bit, we built user-deformed and self-actuated 1D, 2D, and 3D EXHI-bit prototypes involved into a decision support system for architectural integration in an urban environment. The complete scenario consists of doing the following two steps: (1) choosing a building, and (2) integrating the building into the area and making a decision on both its precise position and its precise configuration (e.g. number of floors). Each step uses different EXHI-bit interfaces/prototypes. For each of the three designed prototypes we developed a dedicated application.

6.1 Step 1: Choose a building

6.1.1 Surface expansion prototype. The first prototype (Figure 8) enables surface expansion, i.e expansion in two dimensions. The prototype consists of a grid of 5x7 units: expansion ratio of 241% (153.3% in one dimension, and 157.14% in the other), area from 201.6cm^2 (fully retracted) to 485.76cm^2 (fully expanded). The prototype is self-actuated. The surface is framed by four actuators, two short and two long ones. From the fully retracted configuration, the surface entirely expands in 4.34s.

6.1.2 Application. In this application, the user has to select a building from a database by visualizing its global shape and its textual documentation on a tablet (Figure 8). First, the shape of the current building is displayed at the center of the tablet. A direct touch interaction, coupled with an arcball paradigm, allows the user to observe the building from any point of view. By clicking the left button, via direct touch too, the user switches between buildings. Second, the user can display information about the building by clicking on the right button. This makes the tablet expand in width, displaying textual information *next to* the visual space of the building shape. This allows us to display additional information on demand without overlapping the main display area.

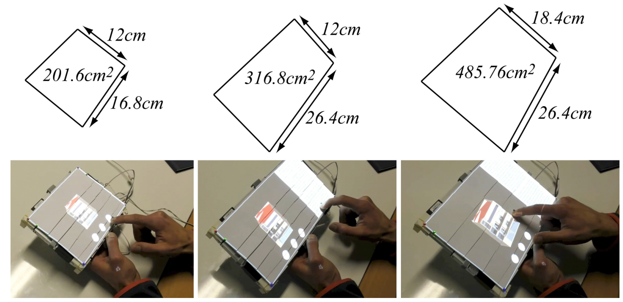

Figure 8: Choose a building, prototype 1. *left*: A building shape is displayed at the center of the tablet, and the user manipulates the 3D object. *middle*: The tablet expands in width for displaying textual documentation. *right*: The tablet fully expands for scaling the entire display, and for zooming on the building and the textual documentation.

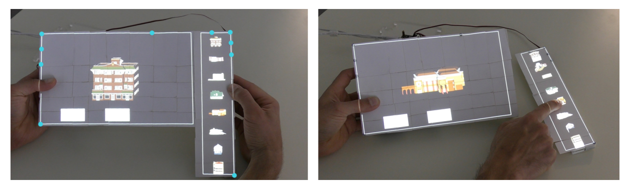

Figure 9: Choose a building, prototype 2. *left*: A building shape is displayed at the center of the tablet. A user switch buildings (left button), or adds a thumbnail of the current one (right button) in the right palette. The latter expands for displaying the entire thumbnails collection, resulting in a right-angled interface. *left*: Tracking markers are highlighted (blue dots). *right*: The palette is detached. Direct touch is still supported.

A middle button is assigned to completely expand the tablet, creating a zoom of the entire display. The tablet can thus morph from a small format (similar to the ipad mini format) to a larger format (similar to a laptop monitor) enabling the display of more information for looking at the details.

6.1.3 Linear and surface expansion prototype. The second prototype for step 1 consists of two combined EXHI-bit prototypes (Figure 9-*left*). We enhance the previous surface expansion prototype (Figure 8) by combining it with an EXHI-bit prototype enabling linear expansion (i.e expansion in one dimension only). The linear expansion prototype is made of 7 units. Its expansion ratio is 157.14%, with a length from 16.8cm to 26.4cm. The prototype is self-actuated thanks to a long actuator attached to the longer side. The resulting combined prototype defines a right-angled interface and is fully self-actuated. The two EXHI-bit prototypes can expand independently and are detachable thanks to a magnetic hinge (Figure 9-*right*).

6.1.4 Application. Extending the previous application, the user can make a list of candidate buildings before selecting one of them. By clicking the right button, the user marks the current building as interesting and its thumbnail appears

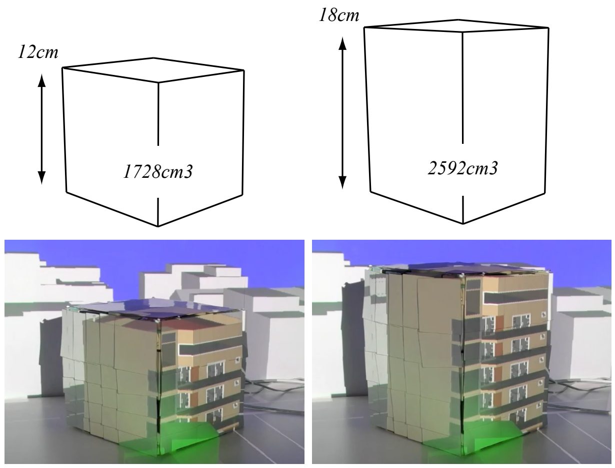

Figure 10: Integrate the building, prototype 3. A town is displayed on a two-plane workbench, and the building is displayed onto the expandable cube. *left*: The cube initial shape. *right*: Two more floors.

in a palette on the right. The palette of thumbnails expands in length in order to always display the entire collection of thumbnails. When enough buildings have been selected, the user detaches the palette. Detachable surfaces provide several identified benefits [4, 7]. By selecting a thumbnail on the detached palette, the corresponding building is displayed on the tablet: the user can then further explore the global shape of the selected buildings.

6.2 Step 2: Integrate a building

The third prototype (Figures 1-*right* and 10) enables volume expansion, i.e. expansion in three dimensions. The initial shape of the prototype is a cube, made of five faces. Each face is an EXHI-bit surface of 5x5 units. The volume expansion of the entire cube is 361%, from $1728cm^3$ to $6229.5cm^3$. The prototype is self-actuated, with the same principle as the first prototype. As all the edges are actuated, the prototype uses 12 short actuators. The prototype fully expands (from fully retracted) in $4.16s$.

6.2.1 Application. This application is an immersive application, i.e we aim at giving the users the illusion that the urban environment is present in front of them. For this, we implemented the Head-Coupled Perspective technique, i.e. the viewpoint projection is based on the position of the user's head, as in Figure 10. This environment is projected on five different planes. First, the town is projected onto a table, in front of which the user sits. In order to provide an optimal perspective of the town and the skyline, we also project the town on a vertical plane at the end of the table. Then, for providing the illusion that the building "is" the box, we project the building and the town on each face of the box which is in front of the user (three faces most of the time).

In this application, the user sees the building he has chosen during the first step of the scenario as well as a part of the town. As the building is displayed onto a tangible box, the users can change its position and orientation by directly interacting with the box. By pressing a button on a keyboard, the user can add floors, making the box expand and adapt (Figure 10). By pressing another button, the user increases the building size, zooming in on the entire environment. At any time the user can move both his head and the building. This allows him to have a good overview of the integration, and then to make a decision on (1) where to position the building, and (2) how many floors should the building have. As the object of interest (the building) is inside a box whose faces are as close as possible to the object faces, **a major benefit is to drastically decrease the conflict between visual accommodation and convergence**. Indeed in the application, the building facades are superposed with the cube's faces.

6.3 Synthesis

Using applications that include novel shape-changing interfaces, we demonstrate the versatility and generality of EXHI-bit. In any expansion status, the three user-deformed or self-actuated EXHI-bit prototypes support direct-touch interaction and are rigid enough to be manipulated and hand held.

Though we have not done any formal evaluation of the applications, in order to gather initial impressions we asked three architects to comment on the scenario. They made several useful comments on the EXHI-bit prototypes in the context of their everyday tasks. In particular on the 3D expandable prototype, one architect conceived the resulting mixed (physical/digital) mock-up as a tool supporting the creation process. The two other architects proposed two usages: (1) to present the various alternatives to non-expert users during the early step of a large urban project; (2) to share solutions designed by different architectural firms using multiple 3D expandable prototypes in order to study various alternatives for the overall design of the area.

7 IN THE HANDS OF USERS

As EXHI-Bit aims at prototyping for experimentally evaluating expandable interfaces, we put an EXHI-bit prototype in the hands of users for gathering comments on expansion. We recruited 10 participants from the local university. All of them were right handed and frequent users of computers and touch devices. They first interacted with the expandable tablet of Figure 8. As an example of a simple GUI on an expandable tablet, a list of items was displayed when expanding the tablet. The expansion was controlled manually (user-deformed tablet) or automatically, triggered by a button (self-actuated tablet). After gaining experience with the tablet (opening/closing and selection of items with the finger) we then asked participants if they would like to possess such an expandable surface, and for what reason. 8/10 participants would like to possess such a device, and all see benefits in expansion:

7.0.1 Potential for adaptation to the environment.

All of the participants expressed the need for a single device, adaptable in size to the environment e.g. "small in my pocket when I'm walking, tablet size in the public transportation, and monitor size at home for watching movies".

7.0.2 Potential for adaptation to the task.

All the participants talked about the adaptation to the task related to the display space. They proposed to display additional information or tools. Less expected, 2 participants proposed to link the type of expansion transitions (manual or actuated) to the type of additional information (e.g. the information criticality). For example, "documentation or news could be open manually, while notifications could be opened by the system". They also argue that, with expansion, additional information could be greater and more precise. The same participants also noticed that the place of the additional information or tools is critical. For example, "when you use a software, the tools are on the top while the notifications appears on the right". One participant suggested expansion in tabs that are smaller than a complete edge, like many drawers (Figure 6-*left*), each one containing different kinds of additional information or tools.

7.0.3 Potential for adaptation to the user.

Not expected, 3 participants said that expansion could be used for adaptation to the user: "Larger screen for better reading for ederly users", "smaller screen for the small hands of the children", and "screen size adapted to the user expertise, e.g more functionalities for experts imply a larger screen, maintaining the same working space resolution for both experts and novices".

7.0.4 Potential for interaction.

5/10 participants proposed to link the expansion gesture to a "zooming action", giving the example of reading a map. Actually, after discussion, it was not a zooming command that they meant. Participants wanted to "see a larger part of the map without loosing resolution". Indeed, zooming with a map application, like in Google maps, is not continuous: labels and base maps change in a discrete way, making jumps and sudden disappearances. With expansion, participants expected to "open" the map, and obtain more information without loosing the current labels and base map. Two participants mentioned the potential of input interaction in games. For example, manual lateral expansion "could be a new way of reloading your gun in FPS games", or "I could expand my tablet for passing from a normal character (when the tablet is retracted) to a new character with extra powers while I am still interacting with my thumbs".

8 CONCLUSION

In this paper we presented EXHI-bit, a new structure for prototyping handheld interfaces that expand in 1, 2, or 3 dimensions. Unique shape-changing prototypes have been developed, including a 3D expandable object and a right-angled interface. The generality and versatility of EXHI-bit enable us to concretely explore the large design space of shape-changing interfaces. Indeed, with EXHI-bit prototypes, the users could hold physical expandable interactive objects that can be experienced in context with application tasks. The feedback from 10 users who have interacted with an EXHI-bit expandable tablet define vision on the use of expandable tablets in our everyday life. With EXHI-bit we can embark on this experimental exploration of the design space of shape-changing interfaces by conducting experiments on novel self-actuated and user-deformed expandable objects. Specific areas in the design space must be explored further in a systematic way by varying parameters along design dimensions (e.g. trigger, control, constraint) of shape change. Our hope is that this work will motivate others to use EXHI-bit (fully available to be reproduced) for experimental exploration of the design space of shape-changing interfaces.

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