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Pauline Olivier, Renaud Chabrier, Damien Rohmer, Eric de Thoisy, Marie-Paule Cani. Nested Explorative Maps: A new 3D canvas for conceptual design in architecture. *Computers and Graphics*, 2019, Special Section on SMI 2019, 82, pp.203-213. 10.1016/j.cag.2019.05.027 . hal-02158131

HAL Id: hal-02158131

<https://hal.science/hal-02158131>

Submitted on 17 Jun 2019

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Nested Explorative Maps: A new 3D canvas for conceptual design in architecture

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Abstract

In this digital age, architects still need to alternate between paper sketches and 3D modeling software for their designs. Indeed, while 3D models enable to explore different views, creating them at very early stages might reduce creativity since they do not allow to superpose several tentative designs nor to refine them progressively, as sketches do. To enable exploratory design in 3D, we introduce *Nested Explorative Maps*, a new system dedicated to interactive design in architecture. Our model enables coarse to fine sketching of nested architectural structures, enabling to progressively sketch a 3D building from floor plan to interior design, thanks to a series of nested maps able to spread in 3D. Each map allows the visual representation of uncertainty as well as the interactive exploration of the alternative, tentative options. We validate the model through a user study conducted with professional architects, enabling us to highlight the potential of *Nested Explorative Maps* for conceptual design in architecture.

Keywords: Sketch-based modeling, Conceptual design, Interactive geometric modeling, Architecture.

1. Introduction

Since the advent of digital tools, architects were asked to use specialized, technical Building Information Modeling (BIM) software, such as *Revit* from Autodesk [1]. These applications enable them to design 3D buildings while precisely specifying each detail, and pass them over to the next actors along the construction chain, after validation by clients. Unfortunately, in addition to a steep learning curve, professional software does not necessarily favour creativity. Indeed, drafting each model may take several hours since many mandatory details need to be specified, from precise dimensions of each element to choice of construction material. This cumbersome modeling stage is not ideal in the creative design phase of a project, and often leads professionals to reuse elements

from a former project rather than designing adapted ones from scratch. Moreover, the fact that some parts of the building may still be rough place-holders, and that several possible alternative versions are still envisioned, cannot be visually represented. Therefore, in practice, architects alternate between manual drawings and digital software. While the use of paper and pen allows for a more global and natural vision at the design stage, and also enables to indicate uncertainty through lighter strokes or over-sketching, this comes with the usual flaws of paper and pen: each sketch represents buildings under a single, static view, progressively adding details must be compromised with sketch readability and jointly modeling the exterior and the interior of a building can only be done to a certain extent. Moreover, after a few concept sketches are drawn, design needs to be re-started from scratch with 3D software, sometimes enabling the late detection of strong inconsistencies that need to be solved along the way.

In this work, we tackle the problem of proposing new 3D modeling paradigms, dedicated to satisfy the archi-

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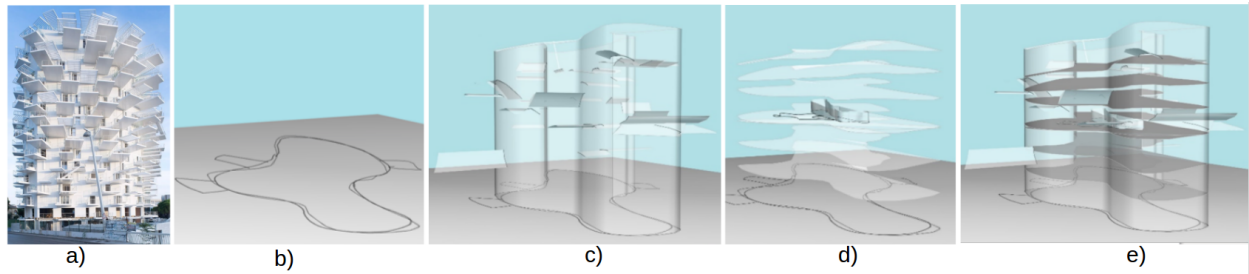


Figure 1: Nested Explorative Maps can be used to quickly draft and explore architectural models. (a) Inspiring photograph: Sou Fujimoto’s White Tree building; (b) Ground map showing two alternative designs; (c-e) Nested 3D canvases, enabling the progressive refinement of the outer and inner parts of the building in less than 10 minutes.

tect’s needs at the conceptual stage of design. This research involved a collaboration with a professional architecture agency, the SCAU agency in Paris, enabling us to conduct two user studies: a pre-user study aimed at identifying the main needs, and a final validation experiment after proposing and developing our new concepts.

In addition to usability and enabling free-form modeling, the first need expressed by architects was to be able to draw in 3D, i.e., the ability to change viewpoint while using their own rough strokes enabling to represent uncertainty as easily as with paper and pen. The second need was being able to model from coarse to fine, i.e., to quickly draft the general view of a building while being able to refine it progressively by adding the relevant details in any appropriate order. The last and most challenging request was being able to interactively explore the different options indicated within the drawing, for each element of the building. Note that this brings a new challenge to sketch-based modeling systems, namely turning the user drawing into an interactive exploration tool rather than merely extracting a single 3D model from it.

We introduce the concept of *Nested Explorative Maps* (NEM). The user is asked to draw and progressively refine a 3D sketch built as a hierarchy of nested and deformable 3D canvases – such as the ground surface of a building, its facade, or inner floors – and some associated maps that convey the original user’s strokes, as well as the information of local uncertainty expressed through over-sketching. Thanks to these maps, alternative architectural options can be “explored” in the sense that the multiple user strokes are used to define and refine preferred positions for each of the 3D canvases, enabling

the user to progressively move and deform them to the most relevant design. At any stage, the user can either edit a map, create a new 3D canvas, or select and move any existing element to a new tentative position on the underlying map, while the consistency of nested details are automatically maintained.

In addition to the concept of NEM itself, our main technical contributions include:

- A recursive solution for creating a 3D sketch by drawing on semi-transparent 3D canvases, themselves extruded from user’s strokes interpreted as footprints – with the associated visualization and editing tools;
- A method, based on local attraction to dense stroke regions, for enabling interactive navigation through the alternative designs that the nested sketch visually suggests. This navigation may not only drive displacement, but also free-form deformation of the nested 3D canvases carrying the user’s strokes.

An example of a conceptual design draft, efficiently created by professional architects is illustrated in Fig. 1.

2. Related work

Our work is related to sketch-based modeling in Computer Graphics, with an application in architecture. Since we do not aim at designing a single 3D model from a sketch, but rather at providing a new way to create and explore 3D architectural sketches, we review both standard

sketch-based 3D modeling and methods aimed at creating 3D sketches. Our review mostly focuses on works dedicated to architecture. The reader can refer to [2, 3] for more general surveys.

2.1. Sketch-based 3D modeling

3D modeling systems in Computer Graphics have ranged from general, interactive systems that limit the number of priors on the shapes being modeled, to dedicated systems strongly based on priors, and therefore dedicated to specific types of objects. While the former usually require interactive sketching from different viewpoints [4] and/or user intervention to help interpreting the sketch [5], relying on priors eases 3D reconstruction and often enables 3D shape inference from a single sketch. Among systems based on priors, some rely on hypotheses on the nature of the input sketch, eg. the use of design sketches [6] or sketches depicting curvature lines [7] while other methods focus on hypotheses on the 3D surface to be created, such as in the case of developable products [8, 9, 10].

Sketch-based modeling methods tackling general, man-made shapes do not fit our goals. Indeed, they do not handle specific features of architectural models such as for example, enabling to sketch details as 2D features before expanding them to 3D – eg. for designing the facade of a building, or allowing the design of nested structures such as inner floors. Although mostly used for garments, dedicated methods for developable surfaces have been illustrated with architectural examples [8], but restrict the user to developable facades and roofs.

To our best knowledge, only three methods were specifically proposed for interactive sketch-based modeling of architectural models. The first one [11] is dedicated to the interactive design of the exterior of buildings in immersive environments. In terms of shapes, the method is restricted to planar and cylindrical primitives. The second method [12] classifies elements of a user’s sketch into basic categories and use a database to infer for each element, the closest 3D model of its category using the maximum likelihood. An iterative refinement mechanism enables the user to use coarse to fine design. The third method [13] combines a sketch-based interface with procedural modeling of buildings. It trains a convolutional neural network to associate procedural models of buildings based on pre-existing architectural elements

with a user’s sketch. The approach allows coarse to fine refinement of the model, and offers the user an interactive choice among a small set of selected designs proposed by the system. While very effective for quickly authoring a set of nice-looking buildings for a virtual city, this system does not authorize the design of new, free-form shapes, nor enables the joint design and exploration of the interior and exterior of buildings.

2.2. Creating a 3D sketch from 2D strokes

As illustrated in [14], sketches are often able to convey a given shape much better than the corresponding 3D model. Therefore, they are massively used – even in 2D – at the earliest stages of design. In Computer Graphics, a number of works tackled the problem of creating a design sketch that lives in 3D, instead of constructing a 3D model. ILoveSketch [15] and EveybodyLovesSketch [16] enable users to draw curves directly in 3D and to refine a 3D sketch using gestural interaction. Other methods still rely on 2D input strokes while enabling the user to navigate, by either providing automatic interpolation between 2D sketches representing different viewpoints [17], or by automatically augmenting user’s strokes to 3D. This can be done by either using priors on the type of shapes being drawn [18] or using annotated 3D models to help embedding the 2D user’s strokes in 3D [19, 20]. In this context, a few methods, described next, specifically tackle design sketches in architecture.

Mental Canvas [21] pioneered the idea of drawing strokes on semi-transparent 2D planes (or canvases). After interactively placing the latter in 3D, the user can draw, but also get strokes projected from a canvas to the next, enabling the easy creation and visualization of 3D sketches. This concept of canvases was later extended to enable the embedding of images in addition to user strokes, in the context of cultural heritage applications [22, 23]. Another extension of Mental Canvas, called Insitu [24], focused on conceptual design within the target natural or man-made 3D environment. The representation of the actual site is created by merging several types of data (elevation map, photographs, aerial map, map of the site), while an user interaction similar to Mental Canvas allows conceptual design directly on the spot. In contrast, SmartCanvas [25] dynamically interprets the 2D user strokes to place them within co-planar groups, and construct 3D polygonal surfaces from them, based on

adjacency relationships. The user may at any time, accept, modify the inferred relationships, or create new ones. An optimization algorithm is used to build the idealized 3D surfaces that approximate the user’s strokes. The model is rendered using a non-photorealistic rendering method to give it the aspect of a drawing, but the initial user strokes are not kept.

In our approach, maps are defined directly on 3D surfaces that act as general *3D canvases* on which the user draws. As they do not restrict the strokes to be drawn on 2D planes, they enable to design buildings of arbitrary free-form shapes. Our method also meets a number of criteria defined by professional architects, defined next.

3. Methodology and overview of our framework

We conducted a one week pre-study at a professional architecture agency [26]¹ in March 2018, in order to study their work flow and identify their current needs. We then evaluated existing solutions with respect to these needs. This led us to the specific design choices at the core of our system.

3.1. Pre-study

We submitted a survey to a dozen of architects, about their design practice with both paper/pen and the software they were the most familiar with. We also asked about the criteria they would like an ideal design tool to meet. This enabled us to identify five main criteria:

Immediate usability (C1) As easy to use as paper & pen.

Coarse to fine (C2) Enabling to create coarse 3D models (eg. not asking for precise dimensions at first) and to progressively improve and refine them, without imposing any specific editing pipeline.

Free-form (C3) Allowing interactive sketching while keeping the user’s free-form strokes instead of over-simplifying them, so that strokes can be used to indicate uncertainty, non-geometric details or any other information (eg. through arrows or hashes).

Uncertainty Providing a way **to represent (C4)** and **to explore (C5)** the alternative options depicted within a given sketch.

3D navigation: Allowing to interactively change viewpoint while preserving all user strokes, and being able to go on drawing from this new viewpoint;

Import: Enabling to import pre-existing, external data (pictures, sketches, terrain elevation, etc).

Based on insight from the architects, we evaluated the capabilities of paper and pen design, and of the digital software used in the agency (such as *Revit* [1] and *SketchUp* [27]), with respect to these needs. We also evaluated the state of the art solutions in Computer Graphics described in Section 2. Among our findings, we noticed that sketching on paper enables users to suggest 3D surfaces from a few rough strokes while using other ones for decoration or to refine the design. This succession of strokes progressively builds the mental image of the model, enabling coarse to fine design. In contrast, 3D modeling software usually requires users to assemble volumetric primitives enabling to materialize the building, with the appropriate dimensions including thickness. Among them, *Revit* requires several months of training and does not allow coarse to fine modeling, although still used by some architects for the early design stage; *SketchUp* is more adapted to prototyping, but still require several days of training and does not handle the representation of uncertainty and the exploration of options. Lastly, while easy to use 3D sketching tools were introduced in recent works, enabling representation of uncertainty through stroke depiction on 3D canvases (criteria C1 to C4), none of the existing solutions meets all the expressed criteria, and more specifically none addresses C5. A summary of these results is given in Table 1 (we omitted 3D navigation which is allowed by all digital solutions, and import which is generally allowed and does not bring major scientific challenges).

3.2. Overview

We present a new solution for 3D sketch creation in architecture, by focusing on achieving all five criteria extracted from the pre-study. We rely on interactive drawing

¹One of the authors of this paper is an architect from this agency.

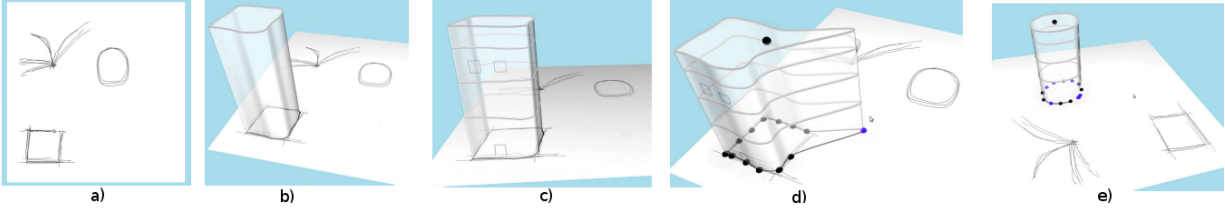


Figure 2: Overview of our tool: the user first sketches on the map of the ground plane, possibly representing uncertainty using over-sketching (a), then he creates a footprint to build a new 3D canvas (b). Visual details and new maps may be drawn on existing canvases (c). At any design stage, the user can explore multiple options by deforming the canvases, which are attracted and snapped to the over-traced strokes on the underlying map (d-e): here a squared tower is dragged and dropped near circular strokes, which automatically deforms its footprint. Note that details such as floors are preserved throughout the explorative deformation.

	C1	C2	C3	C4	C5
Revit [1]	X	X	P	X	X
SketchUp [27]	P	✓	P	X	X
Sketching Procedural [13]	✓	✓	X	X	X
Mental Canvas [21]	✓	✓	✓	✓	X
CHERish [23]	✓	✓	✓	✓	X
Insitu [24]	✓	✓	✓	✓	X
SmartCanvas [25]	✓	P	X	X	X

Table 1: Evaluation of the existing digital tools - including two software used by professionals and recent research solutions - with respect to five of the criteria expressed by architects. "X" means not handled, "P" means partly handled. Our work tackles the introduction of a tool matching all the criteria, and in particular C5, which was never considered so far.

on a digital tablet also serving as screen to keep the interaction as close as possible as paper and pen – thus avoiding any steep learning curve (C1). Our solution enables coarse-to-fine, progressive design (C2). We directly use the free-form user’s strokes as elements of the 3D sketch (C3) More importantly, it allows for the first time both the visualization of uncertainty (C4) and the interactive navigation through the alternative designs suggested by the sketch (C5).

The proposed solution is based on the new concept of *Nested Explorative Maps* with the following contributions:

- 1) Drawing-based recursive creation of a 3D sketch (Section 4), which includes:

Hierarchical organization of 3D canvases and associated maps conveying and interpreting user’s strokes

Dedicated display and editing tools.

- 2) Interactive exploration of the alternative options depicted within the sketch (Section 5).

An overview of our framework, showing progressive creation and exploration, is depicted on Fig. 2.

4. Creating free-form nested canvases and maps

Before describing the details of our approach, let us define the following technical terms:

- **3D canvas** : Surface on which the user can draw a sketch. The term is used by analogy with the traditional artist’s canvas, but in our case, a canvas can be any free-form surface in the 3D space.
- **Footprint** : Vector curve defined from a user’s stroke and serving as basis for the extrusion of a new 3D canvas. Footprints are dynamic elements which can be interactively deformed to allow the exploration of alternative options.
- **Map** : Layer defined on top of a canvas containing both user’s strokes and a texture image which express uncertainty and used to guide subsequent footprint deformation.

An illustration of these elements is proposed in Fig. 2: a) shows the user’s over-sketching strokes stored on a map over a flat canvas; b) displays an additional footprint used to extrude a new 3D canvas; this new canvas is itself associated with a map storing sub-sketches in c); d) and e) show the result of the deformation of a footprint carrying

the associated canvas and map towards another optional design.

4.1. Nested structure

Our goal is to provide a tool enabling to fully draw a building, from a tentative map on the ground surface to facade details and interior design. In our work, we specifically account for the fact that buildings are composed of nested elements, such as floors being within the volume of a building. But we also use the term "nested" in a more general way: although facade details are not geometrically nested within the rough facade surface, their footprints are, enabling us to use a hierarchical structure (the "nested maps" defined below), to represent this hierarchy.

Concept of NEM. The main insight of our work is the fact that most geometrical elements of a building can be designed using extrusion operations from a series of footprints, sketched on free-form canvases: for instance, the external walls can be extruded from a stroke drawn on the ground surface, facade details can be extruded from sketches on the facade, and internal walls can be extruded from footprints sketched on the different floors.

Therefore, we allow the user to recursively create and sketch on a hierarchy of nested 3D canvases and associated maps, each new canvas being created by sketching its footprint. When the footprint is a closed curve, the extruded canvas naturally defines a volume (a generalized cylinder), in which geometrically nested child canvases, such as floors, can be defined. The other children canvases are defined from footprints nested onto the surface on their parent (e.g., to model facade details), which can be used on canvases with both closed or open footprints. Lastly, all footprints can be interactively deformed based on the map lying on their parent, and thus any canvas may dynamically evolve, enabling the user to visually explore alternative designs. To express their dynamic nature enabling exploration, we call this new type of 3D sketch a *Nested Explorative Map (NEM)*.

NEM representation. In practice a NEM is represented using a hierarchical structure carrying three types of elements (see Fig. 3): 3D canvases, maps and footprints. A canvas is stored as a mesh with texture coordinates associated to its map. The map is itself composed of both a set of polylines and a texture image:

- the polylines are 3D projections of the user's strokes, stored in local coordinates with respect to the canvas on which they are drawn,
- the texture image is continuously updated to represent a distance function to this set of strokes.

A footprint is stored, in our implementation, as a spline curve approximating a specific user-stroke. Each footprint is itself the parent element of a child canvas, built from extruding the latter along a specific direction.

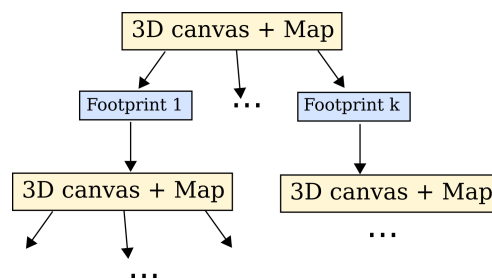


Figure 3: Hierarchical representation used for Nested Explorative Maps (NEM): Each 3D canvas and its associated map can be parents of an arbitrary number of footprint curves, each serving as basis for a new pair of 3D canvas and map.

The use of this hierarchy benefits both visualization and editing:

- The user can at any time choose to display or hide any layers of the canvases in the hierarchy (together with the associated user's strokes and maps). When the user draws, the first surface encountered along the camera viewing direction is considered as the appropriate support canvas for the new stroke. This enables the user to sketch on any of the exterior or interior canvases from the same camera viewpoint, by simply switching canvases display on and off.
- Moreover, the hierarchical structure enables to maintain design consistency throughout the edits, thanks to the attachment of sketched strokes, nested footprints and maps onto the surface of the parent canvas. This enables users to apply their creation and editing operations in any order, including deformations that will help exploring various options in the design.

The reminder of this section details NEM creation and interactive editing operations. The interactive deforma-

tion mechanisms used to explore the uncertain options will be described in Section 5.

4.2. Creating and editing a NEM

The creation of a NEM follows a recursive approach, starting with the ground surface as first canvas. During an interactive session the user keeps alternating between sketching strokes to edit the maps on the displayed canvases, drawing footprints to create new child canvases, and editing the latter (see Figure 2). All these operations are based on free-hand drawing and can be done from arbitrary viewpoint, with any number of displayed layers in the hierarchy. This enables to create and refine any part of the NEM at any time, which is essential at the design phase of a project.

Map sketching mode. In this mode, the user stroke, ie. the polyline captured on the screen space, is projected along the camera viewing direction to the closest displayed 3D canvas. The user can change canvas selection by setting display on or off for each of the existing canvas layers in the hierarchy. Note that for each map, the original user strokes are stored and displayed without any simplification or smoothing steps. This enables us to preserve the depiction style of the architect as well as their usual expression of uncertainty (such as over-sketching a curve or drawing it with dashed lines).

Nested footprint mode. In this mode, the user draws on any displayed canvas, a single continuous stroke, interpreted as the footprint of a new 3D canvas. This footprint can be an open or a closed curve from which the child canvas is extruded along, either vertically, horizontally, or in the averaged normal direction of the support canvas. While verticals and horizontals fit standard architectural design, the use of the additional averaged normal direction allows free-form 3D design.

We chose to use cubic interpolating Catmull-Rom splines to represent footprint curves, in order to help generating smooth canvas surfaces. To provide a better level of smoothing for quickly drawn strokes, the positions of the control points are set using a combination of the drawing speed of the user and the distance between the points of the original stroke. From the user’s viewpoint, sketching fast allows to model smooth curves, while sketching

slower enables the precise design of sharper curves. Having a closed footprint, and thus a generalized cylinder as the associated canvas, is the condition for subsequently adding inner floors. To ease the creation of such footprints, we snap the first and end vertices together if their distance is less than a threshold.

Floor mode. When sketching on a canvas representing a volume (a generalized cylinder), the user’s stroke can be interpreted as a separating surface to allow, for instance, the creation of a new floor. This is done by selecting floor mode, and sketching a line on the cylindrical canvas. This stroke is projected and expanded along the other sides of the canvas surface as to model a closed 3D curve. This curve, that can be considered as a special case of footprint, serves as contour of a new 3D canvas. To limit the total number of polygons, we generate a coarse triangulation of the floor surface from a sub-sampled set of points from the footprint, and a few central points on its medial axis.

Cutting mode. The user can interactively cut canvases by sketching a free-form cutting line over one or several of the displayed canvases, as illustrated in Figure 4. Similarly to scissors cutting paper, the cutting line is expected to span the entire cross-section of the canvases it should cut. Cutting is applied to all the displayed canvases for which this property holds, enabling the user to cut several canvases, embedded within one another or not, in a single cutting gesture. After automatically selecting these canvases, the associated meshes are cut so that the border of their projection on screen matches the cutting stroke.

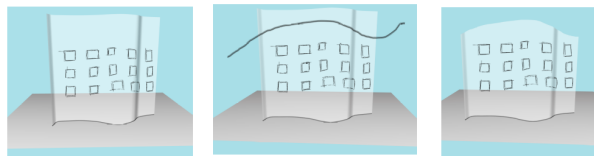


Figure 4: Cutting a canvas with a free-form stroke.

5. Interactive exploration of alternative options

A key point of our method is that the user’s sketches strokes on maps, enabling them to represent uncertainty and alternative options thanks to over-sketching. Based

on their density, the corresponding polylines are used to model a continuous field (stored within the texture image part of a map) guiding and attracting the footprints during user’s interactive manipulation. This enables the user to interactively deform and explore the different options depicted on the maps, using a simple picking gesture to select a 3D canvas and move it around. Indeed, this operation can be applied at any level of the NEM hierarchy.

5.1. Confidence field from a set of strokes

Uncertainty is traditionally depicted using several strokes of various density and thicknesses. Locally, a high density of strokes indicates strong confidence in the fact that an element should be placed there, while sparser ones express uncertainty.

Therefore, the maps we use do not only consist of the set of strokes drawn on the associated canvas, but also of an additional 2D texture image called the *confidence field* F . The latter, computed from the strokes, will be used to interactively attract and deform footprint curves toward high field values, corresponding to dense strokes regions in the map. The confidence field F corresponds to a 2D grid of scalar values, stored as a texture layer associated with the canvas. The mapping we use is the natural (u,v)-parametrization given by the extrusion operation that creates the canvas: u varies along the footprint direction and v varies along the extrusion direction.

At each grid point p , $F(p)$ is computed as the cumulative 2D field generated by the convolution of a kernel κ along each of the user’s strokes S_i of the current map:

$$F_i(p) = \int_{S_i} \alpha \kappa(p, s) ds \quad (1)$$

where α is the thickness of S_i and the kernel is defined as:

$$\kappa(p, s) = \frac{1}{d(p, s)^3} \quad (2)$$

$d(p,s)$ being the distance between the grid point p and a point s of S_i .

We chose this specific kernel because its integral along a curve (Equation (1)) has a closed form solution (see [28]). This leads to an efficient evaluation, over the grid, of the smooth 2D field $F = \sum F_i$, expressing the local confidence computed from the set of strokes in a map.

In practice, F is computed in an incremental way: the contribution of each new stroke is added, each time a new stroke is created. Figure 5 depicts a map on a floor where user’s strokes are drawn on an inner canvas, and the associated confidence field is shown in red. Note that our use of texture mapping to associate confidence fields to the canvas, in addition to the relative coordinates used to store the user strokes, enable to freely deform the canvas while maintaining the consistency of the associated map.

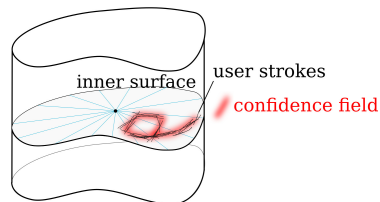


Figure 5: An example of confidence field sketched on an inner canvas.

5.2. Plastic deformation of footprints and canvases

During the user’s exploration of the alternative options expressed by the NEM using drag-and-drop approach, footprints are deformed interactively, which automatically propagates deformation to the associated child canvas and the corresponding sub-tree of the hierarchy.

We aim at modeling the following behaviors for deformable, footprint curves: while being interactively guided and deformed by the user’s interaction gesture, the curve should be attracted towards close-by high confidence regions, expressed by high values of F . Footprints should also tend to preserve their features such as length and curvature under small deformations, but should be able to accommodate more drastic changes of shape to adapt to larger deformations, and remain at its new equilibrium position when the user releases the footprint.

Such plastic deformations can be modeled using a set of mass-particles connected by plastic springs, i.e., springs able to absorb all deformations that exceed a specified threshold, by changing their rest length if needed. More precisely, particles with associated mass, position, and speed parameters are associated with each control point of the footprint (depicted as spheres in Fig. 7). Plastic-springs are set to connect neighboring particles as well as second neighbors, i.e., particles sharing a common direct

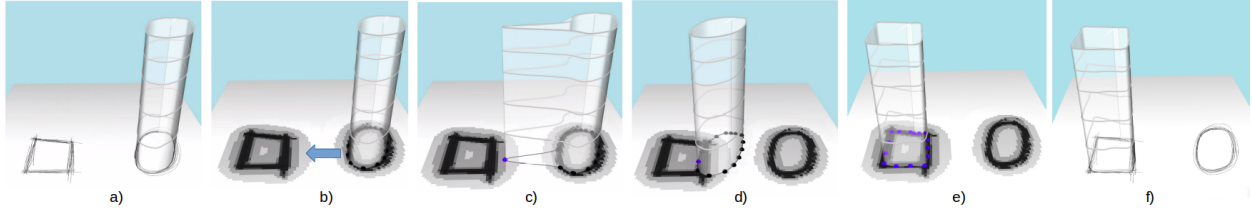


Figure 6: Example of representation and exploration of uncertainty : an initial cylindrical shape with inner floors is interactively dragged by the user and automatically adapts its shape to a squared one as sketched on the ground map.

neighbor, to ensure a better shape preservation when no strong force is applied.

In addition to the usual elastic and friction forces, particles are subject to an attraction potential given as

$$P_{attraction}(p) = \exp\left(-\frac{(F(p)/\sigma)^2}{2}\right). \quad (3)$$

Note that the potential is smoothly decreasing toward zero in the vicinity of the user's strokes. Similarly to deformable contour approaches [29], we consider the associated force that derives from this potential as $F_{attraction}(p) = -\nabla P_{attraction}(p)$. Lastly, user interaction is modeled as a hard positional constraint using a drag-and-drop gesture applied on a particle.

When small deformations are applied to a footprint curve, the described forces lead to a standard elastic behavior, ie. a smooth deformation of the curve, which tries to preserve its shape while best fitting local high confidence values. In reverse, when a large displacement is applied and leads to extreme spring-length elongation or contraction, springs switch to their plastic behavior by absorbing deformations. This is done through a change of their rest length, while the associated elastic force remains zero.

Thanks to this mechanism, the rest shape of the footprint curve is able to evolve. Subsequent deformations will just act the same way on the new curve, enabling users to go on exploring options until they are satisfied.

Note that the deformation associated with these plastic-springs is efficiently computed in the 2D parametric space. After each animation step, the corresponding 3D positions are displayed on the canvas.

Finally, two extra specific behaviors can also be used by the user who can, first, fix the position of some particles to precisely adapt some local deformations. Second, a global rigid translation of the entire curve can also

take place when the displacement of particle exceeds a certain threshold. Note that this global displacement can take place before the user releases the footprint curve, and thus before the action of the plastic-springs.

Figure 6 presents an example of a deformation applied to a nested structure. First, the user depicts the ground surface map by drawing two geometric squared and circular shapes using over-sketching, then he models the circular tower from a circular footprint and generates the associated floors. Next, the user drags some positions of the plastic-springs associated to the footprint toward the squared shape, leading to the adaptation of the entire NEM structure to a new equilibrium position as a squared shaped building. As illustrated in Fig. 7 such plastic deformation can also be applied to child elements on a 3D canvas where a protruding window is moved and deformed from a circular basis shape to a rectangular one. Fig. 8 shows that uncertainty can also be used to express the local shape of a building, in this case in exploring the possibility of a building extension. Finally, Fig. 9 presents other examples of uncertainty representation and the exploration of alternative options.

6. Results and Evaluation

Please note that in addition to the illustrations in the paper, different examples of dynamic use of our system are shown in the accompanying video.

6.1. User study

We validated the NEM system through a user study conducted with professional architects. Our goal was to test the following hypotheses:

- H1 : The user's free form strokes are preserved during the creative session.

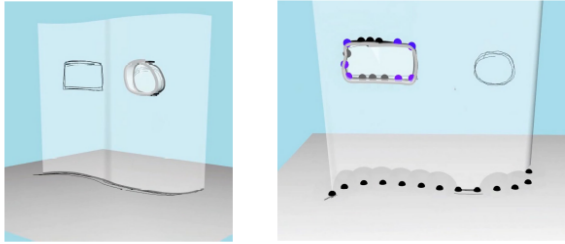


Figure 7: Exploring uncertain shapes and positions can also apply to sub-elements: here, a protruding window is snapped either to the circular shape or to the rectangular one.

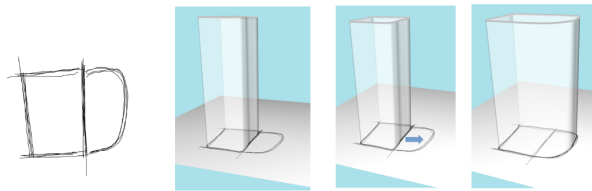


Figure 8: Uncertainty representation for the footprint of a canvas and exploration through interactive local deformation. The footprint gets locally attracted to a new part of the map.

- H2 : The system allows a coarse-to-fine design and does not impose any editing pipeline.
- H3 : The system allows uncertainty to be represented, as well as the interactive exploration of the depicted options.
- H4 : Creating a 3D sketch with NEMs is faster than using any existing professional software.
- H5 : The tool is more suited to the creative design phase of a project than the industrial software our users are familiar with.

The experiment conducted with each of our users was composed of three stages:

1. Explanation of the concept and interactive demonstration (5 mn);
2. Learning phase: exercise of reproducing a basic model presented in the demonstration (5 mn);
3. Creation of an imaginary model (5 to 10 mn).

For the last stage, architects had the choice to create their model from scratch or taking inspiration from examples of creative architectural projects containing free-form building shapes that we believed to be hard to model using standard industrial software. These visual references are available in a supplementary document. During this stage, the system was regularly saved as well as screenshots taken. At the end of the session, users were asked to answer a survey and giving scores from 1 (strongly disagree) to 5 (strongly agree) to validate or refute our different hypotheses. Note that the question sheet given to the participants is provided as a supplementary material. To validate the convenience of the tool with respect to the pipeline in the tool the architects were normally using, we asked the users to compare our prototype with their usual software, and give the name of this software. They were then able to express free comments.

6.2. Experiment setup

Our prototype was tested by 17 professionals, including 13 males and 4 females from the age of 23 to 57 years old. This group included 2 students in architecture and 15 professional architects, with experience ranging from 0 to 40 years. 16 of them were right-handed and 1 was left-handed. Each session lasted about 15 minutes.

6.3. Results of the user study

Fig. 10 shows the progressive construction of a 3D sketch done by an architect with our system during the user study, and Fig. 14 some other creations made during the same study.

After the user study, we calculated the mean and standard deviation of the answers obtained for each hypothesis. Fig. 11 displays the charts associated with these scores.

From their comments, the architects perceived, in general, the tool as an original and impressive "augmented paper", able to replace paper and pen as well as any digital software at the creative design phase of a project. They particularly liked the direct relationship between sketching on a tablet (serving also as a display screen), and the resulting 3D model, as well as the general freedom of modeling even complicated shapes in 3D. The system was found to be playful, and very convenient to draft ideas, explore and communicate them.

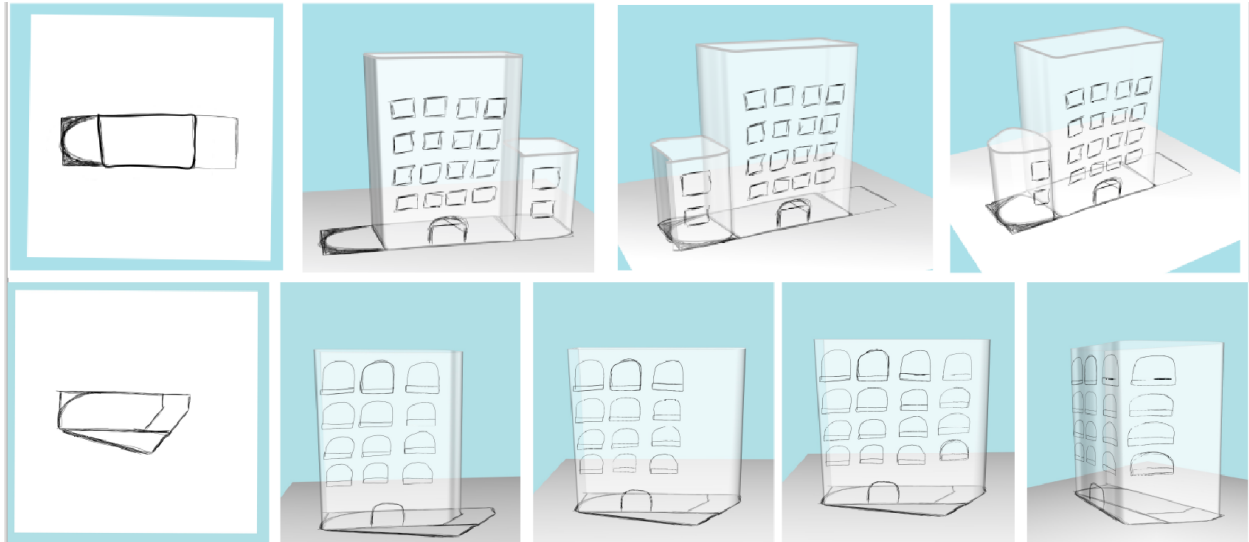


Figure 9: Two examples of uncertainty representation and the exploration of alternative options

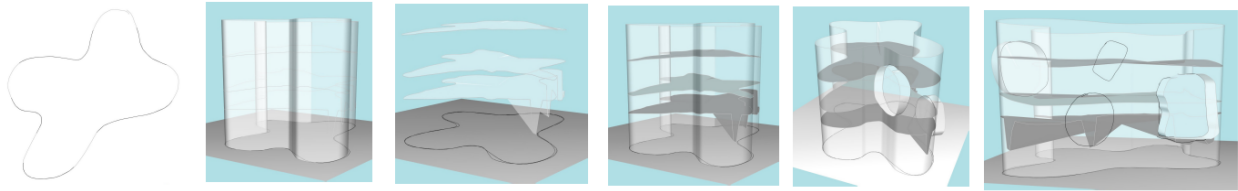


Figure 10: Progressive construction of a 3D sketch by an architect, during the user study.

The preservation of the original drawn strokes (H1) was appreciated by most of the users. Being accustomed to work on software that replaces the strokes by simple vector shapes, designers found it interesting to keep their rough strokes and were able to create free-form shapes as illustrated in Figure 10.

Users confirmed that coarse-to-fine design (H2), with in particular the simultaneous design of the outside and inside parts of a building were possible. Being able to see at the same time the inside and the outside parts, thanks to our semi-transparent canvases, was highly appreciated among users, but the lack of precise dimensions disturbed two of the participants.

The representation of uncertainty and the exploration of options (H3) were much appreciated. Participants men-

tioned that keeping the rough aspect of a paper sketch was very important to communicate, sketch ideas and approximate a sketch shape with several strokes. The possibility to explore multiple options has also been seen as a positive addition, bringing more freedom to the modeling process. Furthermore, one architect pointed out that the combination of the elasticity and plasticity behavior was well adapted to their needs.

Even though our prototype system provides much less functionality than professional software, the participants were able to achieve their first designs in less than 15 minutes using all operations allowed by our method, and validated our hypothesis (H4). Some of the functionalities such as the cutting operation, or the creation of a floor inside a building, were qualified as intuitive by several

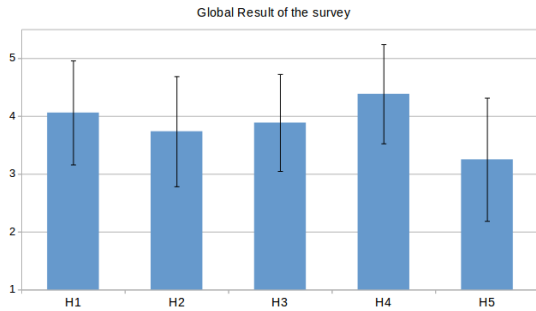


Figure 11: Global result for the hypothesis in the survey (in blue the mean value and in black the standard deviation).

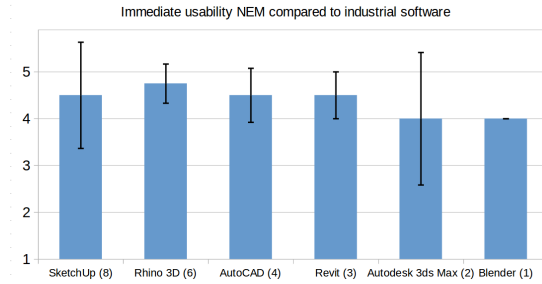


Figure 13: Answers to the immediate usability question (H4) among users of different software.

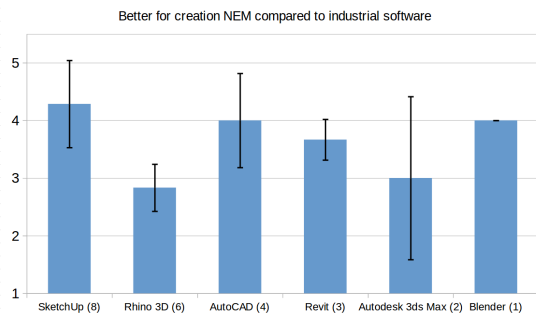


Figure 12: Validation of hypothesis H5, i.e. comparison as a creative tool with the preferred software chosen by each participant. The indication below each bin indicates the number of users who compared NEM to this specific software.

participants.

Hypothesis H5 received lower results on average with larger variations. We could note that these variations were largely influenced by the habits of the participants with respect of their preferred software. Fig. 12 depicts the scores associated to H5 with respect to their preferred industrial software. One could note that participants using Rhino 3D were associated with the lowest scores, and considered their usual software as equally creative than the NEM approach. In comparison, the immediate usability of NEM was homogeneously acknowledged, independently of their habits as shown in Fig. 13 (Note that we were surprised to discover that professional architects were not only using standard BIM tools such as Revit, but also more generic 3D creation tools from 3DSMax to Blender).

Lastly, the experience of the participants and their position in the agency had indeed some influence on their perception of the tool. While we had too few participants for developing a quantitative study, we were able to observe the following: experienced architects, who had been subject to a longer training with pen and paper, were enthusiastic about the general idea of the tool, and especially at the idea of being able to explore uncertainty. They strongly encouraged further development of the tool towards creativity – as for instance enabling the creation, exploration and progressive refinement or arbitrary, free form shapes. In contrast, while architecture students and beginning professional architects particularly appreciated the effectiveness of the tool for generating draft buildings, compared to their usual technical software, they less frequently mentioned the importance of being able to represent and explore uncertainty.

6.4. Discussion

While our prototype was generally quite well received by users, we are aware that the current implementation could be optimized and that several useful functionalities are missing. In particular, several users complained about the few seconds of latency during the exploration of uncertain options, due to our CPU implementation of confidence maps. The models we chose for both the confidence field and surface deformation also have an impact on the expressiveness of our system. For instance, overlapping strokes sketched by the user contribute currently to the confidence field based on their thickness, but cannot be considered as two independent, mutually exclusive options. Similarly, we did not implement any detection

mechanism for hatching strokes, while they could be used to express specific information such as orientation or curvature of the underlying surface patch. Moreover, while the architects had stressed the importance of being able to import external data in the pre-user study (eg. pre-existing and height-fields for the terrain, texture for a facade), this was not implemented in our prototype. This capability would be easy to add but would require an interactive tool to help mapping such data onto 3D canvases at the appropriate orientation and scale.

There are still many directions to explore for further improving our method. Firstly, enabling the user to extrude a footprint along a free-form path drawn using another stroke, like in [4], would extend the creativity of our system and allow to create free-form pieces of architecture such as the Sydney Opera House. Secondly, the current cut operator should be extended, for instance for being able to cut holes within a canvas. Thirdly, being able to dynamically adapt the sampling of the deformed footprint, or the use of more general deformation modes for any curves could allow to model a wider variety of shapes.

Lastly, the main limitation of our current tool is the lack of connection with the industrial software. While our prototype will soon be available online, and architects will be able to use it at the early stage of design, the user is currently not able to assign dimensions to any elements of a NEM and export them to another tool at the end of the creative design stage. In agreement with the architect agency mentioned in the user study, we believe that the possible adoption of our tool by professionals at a larger scale would benefit from its implementation as an add-on of an existing prototyping software such as Rhino. Thus, standard quick prototyping methods could be leveraged with confidence fields stored as texture maps on top of surfaces, allowing to navigate through uncertain options.

7. Conclusion

We proposed a new type of 3D sketches dedicated to the early design phase in architecture, which is hardly covered by standard industrial tools. Based on a pre-study of user needs, we were able to introduce the concept of *Nested Explorative Maps*, enabling the recursive creation of maps based on user-drawn strokes on nested free-form

canvases, the interactive display and the interaction with these semi-transparent canvas layers.

Our tool is the first one, to our best knowledge, able to interactively explore the different design options depicted within a 3D sketch. This was done by assigning a plastic behaviour to our 3D canvases and enabling the user to move their footprints on a map where stroke density triggers attraction. As validated by our user study, being able to represent the uncertainty and navigate among different options is a real improvement at the early stages of conceptual design.

In future work, we would like to explore the generalization of our nested hierarchy mixing free-form canvases and maps depicted on them to other applications, such as 3D sketching for product design and interactive depiction in sciences.

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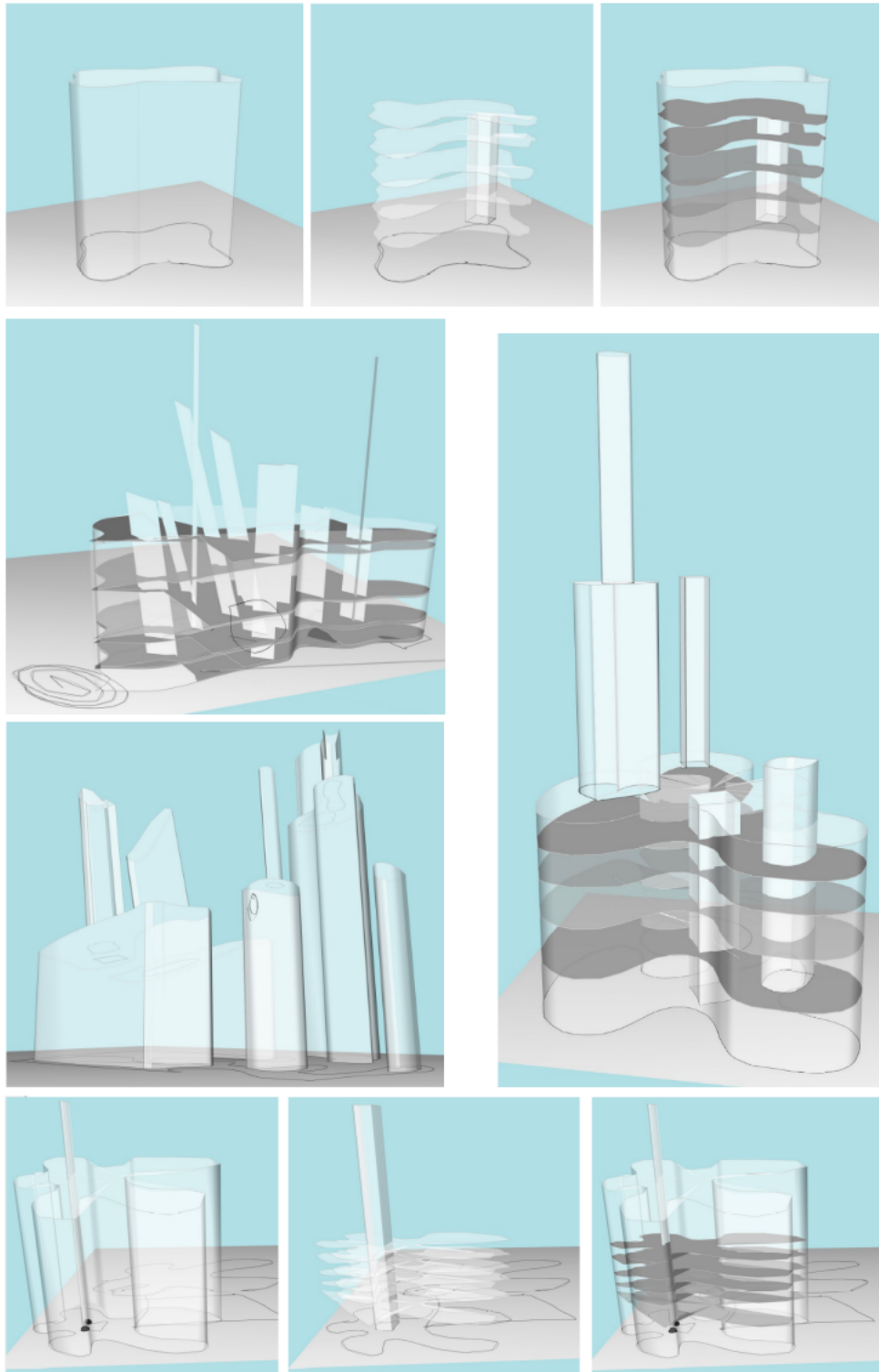


Figure 14: A few results of the creative designs made in the last stage of the user study.