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Case study

Expeditious illustration of layer-cake models on and above a tactile surface

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Too often illustrating and visualizing 3D geological concepts are performed by sketching in 2D mediums, which may limit drawing performance of initial concepts. Here, the potential of expeditious geological modeling brought by hand gestures is explored. A spatial interaction system was developed to enable rapid modeling, editing, and exploration of 3D layer-cake objects. User interactions are acquired with motion capture and touch screen technologies. Virtual immersion is guaranteed by using stereoscopic technology. The novelty consists of performing expeditious modeling of coarse geological features with only a limited set of hand gestures. Results from usability-studies show that the proposed system is more efficient when compared to a windows-icon-menu-pointer modeling application.

1. Introduction

Three dimensional visualizations of geological constructs are common in many geo-related fields since these communicate spatial relationships and possible structural configurations of geological objects effectively (Lidal, 2013; Turner, 2006). Currently these visualizations are conveyed by 3D illustrations drawn on 2D media using conventional computer input such as mouse and keyboard. Recently-developed approaches propose 2D sketch-based systems to enable rapid geological modeling of terrains and stratigraphic elements (Lidal, 2013). However, advanced stereoscopic visualization systems and new gesture-based spatial interaction systems using 3D sensing technology and touchscreens (Galyean and Hughes, 1991; Schkolne et al., 2001; Keefe et al., 2001; Piper et al., 2002; Hilliges et al., 2012) could usher in even more expeditious means to rapidly build or illustrate geological model, via direct manipulation.

Geological illustration must take into consideration the amount of complexity to be pictured, which depends on the level of detail required along with the abstraction chosen to represent geological phenomena (Natali et al., 2013; Laurent et al., 2015). For instance, highly detailed geological illustration is a demanding endeavor performed by well-skilled illustrators who need to interact with geologists and iterate over different visualizations to arrive at a desired result, which usually are richly populated with detailed features. This lengthens the process and is an obstacle to quickly exploring alternate scenarios.

However, illustrators can build highly detailed models by starting with more simplified model versions, as a more meaningful model comes up when composing with a series of relatively simple structural elements (e.g., terrains, horizons, elevations or depressions) (Jessell and Valenta, 1996; Laurent et al., 2015). Another advantage of simplified models is that they can be rapidly built, hence, users can quickly deliver an initial composition of the geological model and also propose several alternative structural arrangements.

Therefore, and contrary to highly detailed geological illustration, we approach an early visualization framework that offers a simpler level of detail, where externalizing ideas or concepts of a layer-cake model in the absence of quantitative geological data. These so-called "no-data scenarios" are common in geology (Jessell and Valenta, 1996; Natali et al., 2013; Laurent et al., 2015). In the absence of data, major features (e.g., largest elevations and depressions, large faults and intrusive bodies) of terrains (air–soil interface) and horizons (soil–soil interfaces) are easier to be modeled from scratch. The lack or absence of data requires modelers to focus on global features, which can be complemented when more data become available. Modeling is guided by the qualitative geological knowledge and it may take several rapid iterations to produce the desired result. Qualitative and rough as they are, these externalizations are favored by geologists since they allow valuable insights and hypotheses to be explored without requiring costly terrain surveys and seismic data collection.

The work presented here provides a spatial interaction system that can be used by geologists and illustrators alike to build layer-cake geological illustrations via hand gestures. Our approach to expedite modeling relies on observations that geologists can

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quickly sketch the rough structure of a terrain or of a stratigraphic layer with few strokes (Lidal, 2013). We conjecture that a spatial sketching interface would provide a quicker way to externalize an ideated model by geologists or illustrators. We have explored this modeling principle, examining the geological expressiveness of hand gestures towards rapidly creating geological layered-objects.

2. Related work

Most available geomodeling systems aim to build complex models and are concerned with defining intricate details that reveal geological complexities arising from numerical data. Good examples of this include 3D GeoModeller,[1] EarthVision,[2] Petrel[3] or GoCad.[4] These programs require large amounts of data to build a visualization. The collection and modeling process can take several months to complete a project. These systems are thus not tailored for expressing initial concepts of multiple geometries for rapid communication nor are they suitable for proposing alternative structural arrangements (Bendiksen, 2013).

Several works describe how challenging it is to create computational tools for modeling and visualization of geological structures in windows-icons-menus-pointer (WIMP) environments (Olsen, 2004; Turner, 2006; Peytavie et al., 2009; Wilson, 2012; Lidal, 2013). On the other hand, there are several papers on sketch-based modeling of terrains (Olsen, 2004; Stava et al., 2008; Gain et al., 2009; Hnaidi et al., 2010; Wilson, 2012; Tasse et al., 2014), but only few adopt a sketch-based approach for modeling sub-layers (Natali et al., 2012,2014; Amorim et al., 2012; Lidal et al., 2013). Probably the most notorious work on sketch-based systems for geological modeling is presented by (Lidal, 2013). In his thesis, several sketch-based systems to rapidly model layered-structure geometries were presented. Although different sketching approaches were considered, none of them makes use of spatial interaction systems where hand gestures are used to explicitly model geological content. Although 3D modeling using free space 3D input is not new (Galyean and Hughes, 1991; Schkolne et al., 2001; Keefe et al., 2001; Piper et al., 2002; Hilliges et al., 2012), a gesture-based spatial interaction system to rapidly build layer-cake models has not been developed before for geological illustration. This paper addresses this gap in geological modeling, where an interactive system with stereoscopic display is presented which allows users to directly edit and visualize spatial relationships between geological layers.

3. Spatial interaction system

The proposed system is called GeoCake and it was designed to model heightmap surfaces via swift and expressive hand gestures, using touch gestures to add finer details to surfaces. The GeoCake system uses an interactive table composed of a large 3D screen (Samsung UE55F8000: 55” F8000 Series 8 Smart 3D Full HD LED TV) placed horizontally at waist height (~95 cm above the floor) which is framed with a grid of equally-spaced infrared LEDs, on one side of the frame, paired with photo-receivers, on the opposite side of the frame (Infrared Grid). Touch gestures are detected when fingers block infrared beam paths between LEDs and receivers. To allow for precise 3D interaction, the table is surrounded by 10 motion capture cameras (OptiTrak) that continuously track optical markers placed on a drawing device. Furthermore we use a depth camera (Kinect) to track the head position and also the user's skeleton (Fig. 1). Stereoscopic perception is accomplished through a stereoscopic display using active shutter glasses with polarized lenses together with a depth camera which records the position of the head relative to the screen.

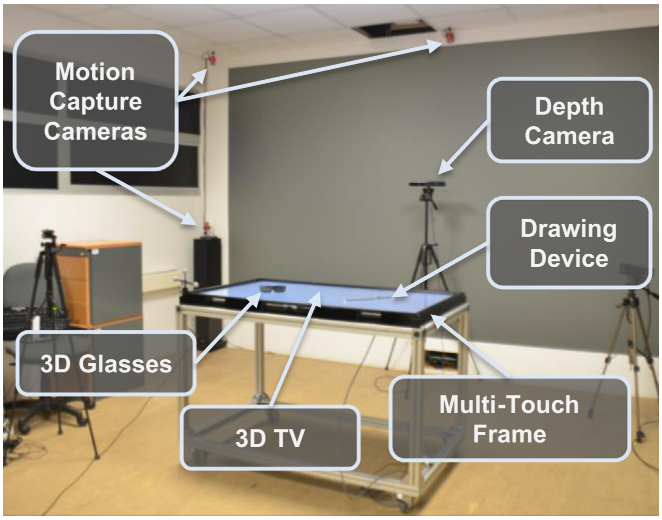

Fig. 1. Hardware setup of the spatial interaction system.

Inside the graphical user interface (GUI), the user visualizes a proxy box inside which geological content is sketched and where handles, placed at its corners, evoke clipping planes (Fig. 2). The GUI also presents a lateral menu for evoking several modeling and visualization functionalities along with a vertical slider to change the surface heights. By interacting with the screen, the modeler can translate, rotate, scale and edit surfaces through touch gestures. When in camera mode the user can perform the geometric transformations, evoke clipping planes and adjust the heights of the layers, while in modeling mode the user can sketch 3D curves with the drawing device and edit surfaces through touch gestures. After sketching the model, the resulting meshes can be exported in *.obj format, thus, allowing any interested user to import the model into game development platforms [Unity3D,[5] Unreal Engine[6]] or further refine and add intricate details in more advanced modeling systems [3D Max,[7] Blender[8]]. The application was developed in Unity3D which allows the dynamic creation of 3D content in real-time and to set up GUIs.

3.1. Stereoscopic visualization

Stereoscopy is a very useful tool for modeling and exploring three-dimensional objects, leading to a better understanding of the 3D content when compared to a flat display (Araújo et al., 2013). Perception of the modeled geological object is achieved by combining a stereoscopic display, a pair of polarized glasses, and a depth camera that detects the position of the user’s head. Even if there are many people around the table, the depth camera chooses the user that is closest to the center of the tabletop screen. Otherwise, the system would generate images of different users, hence, creating a flickering effect.

The system then calculates the user’s custom projection matrix (Kooima, 2008) by updating the positions of the cameras in the scene to the mapped position of the modeler in the virtual world. The system then generates a pair of images, one for each eye and

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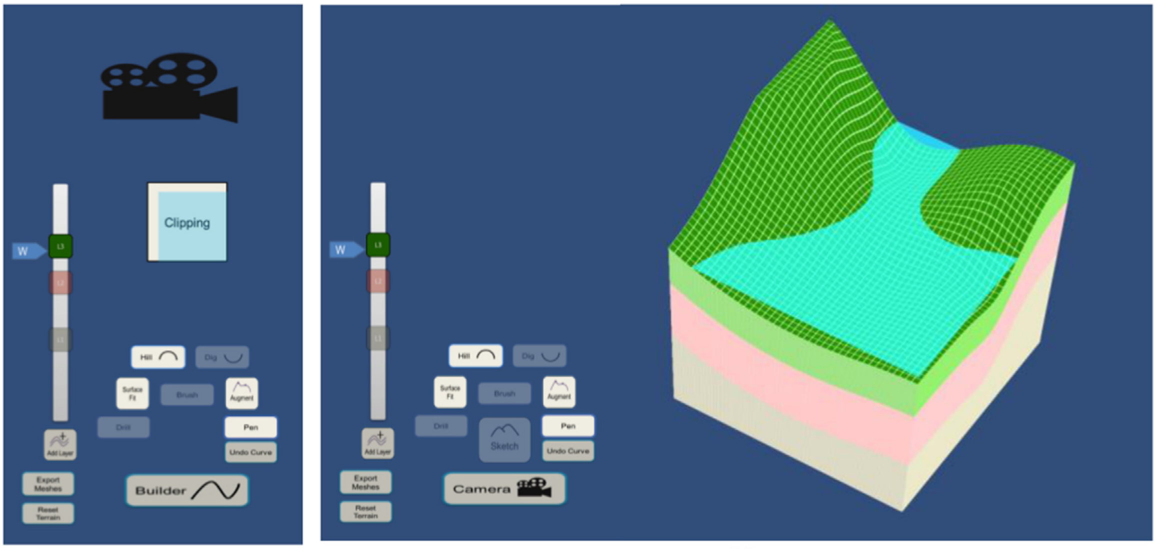
[1] www.geomodeller.com
[2] www.dgi.com/earthvision/evmain.html
[3] http://www.slb.com/petrel.aspx
[4] http://www.pdgm.com/Products/GOCAD.aspx
[5] unity3d.com/
[6] https://www.unrealengine.com/
[7] www.autodesk.com/products/3ds-max/
[8] https://www.blender.org/



(a) (b)

Fig. 2. GUI showing the menu settings for (a) visualization mode and (b) modeling mode.

positioned with a small gap in order to simulate the space between eye positions, providing a spatial perception from the user's own perspective, thus, conveying the illusion that the 3D objects are above the tabletop surface.

3.2. Interaction

Interaction with the system follows an asymmetric bimanual model (Guiard, 1987) which considers the user actions, hand dominance and interaction spaces shown in (Fig. 3). For this purpose, the system requires that the user uses the dominant hand (DH) mostly to perform spatial interactions, in this case, mid-air sketching with a drawing device, while the non-dominant hand (NDH) interacts with the visualization and modeling GUI (Fig. 4). The DH not only manipulates a drawing device but can also perform touch gestures to add surface details. The DH can also be used for translating the proxy box or to complement the rotational and scaling tasks performed in conjunction with the NDH. Clipping the proxy box, choosing the surface layer and alternating between camera and modeling modes are tasks better suited for the NDH.

Either with the DH, NDH or both, interaction on top of the table is accomplished using two types of touch gestures: (i) single tap to select buttons on the GUI or to locally edit surfaces; and (ii) tap and drag to adjust layer height, to perform geometric transformations on the scenario or to slide clipping plane handles.

3.3. Geomodeling

Through the proposed sketch-based interface, it is possible to build two categories of geological models: terrain models and layer-cake models, being the later model composed by terrain, horizons, and layers). Furthermore, these elements can be detailed with geological features consisting of elevations and depressions, e.g., mountains, valleys, rivers, deltas, folds or channels (Turner, 2006; Turner and Gable, 2007; Natali et al., 2013).

Terrains and horizons present spatial continuity, whereas abrupt surface variations are not as common (Caumon et al., 2009). This feature makes 3D sketching a viable geomodeling modality since a 3D stroke also has spatial continuity, while discontinuities can be added later on. Thus, the adopted modeling principle consists of, starting in a scenario with no data (Natali et al., 2013), sketching the overall geologic structure of a horizon or terrain with a very limited set of gesture interactions, either spatial gestures for defining the gross features or touch gestures to add finer details.

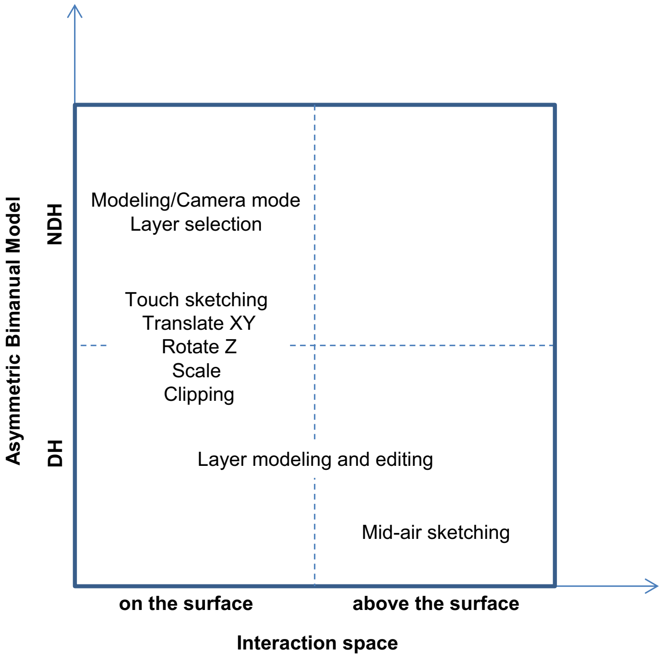


Fig. 3. User actions, hand dominance and interaction spaces of the proposed sketching system.

In particular, a modeling session starts with all the surface layers set to height zero. Each surface is then modeled independently in a bottom-up order, thus the terrain is modeled at last. Since layer-cake models are composed with multiple heitghmaps, it is necessary to address how heightmaps intersect. Here, we constrain each point of the heightmap in the following manner: (i) if the point of the current heightmap gets lower than the homologous point (i.e., points with different height but with the same *x* and *y* coordinates) of heightmap immediately below it, then this point will share the same height of the bottom heightmap; and (ii) if the point of the current heightmap gets higher than the homologous point of heightmap immediately above it, then this point will force the upper heightmap to share the same

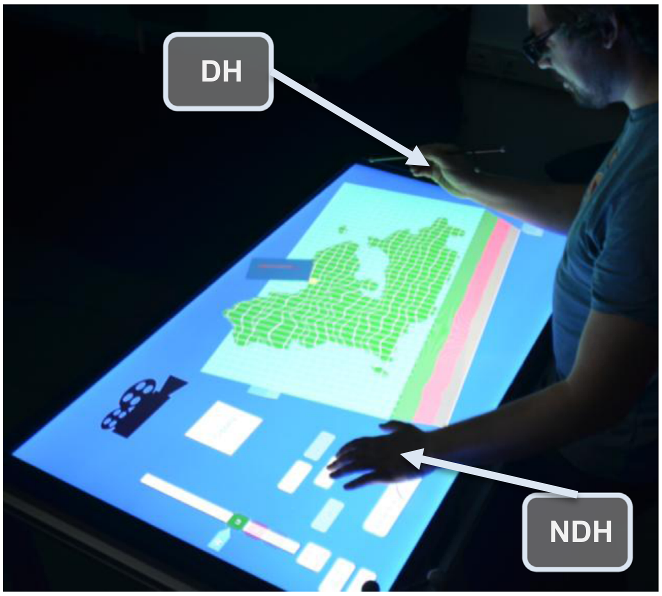


Fig. 4. The DH holds the 3D drawing device while the NDH interacts with the GUI to evoke application functionalities.

height of the current layer. Consequently, modifications of the lower layers may alter the terrain (i.e., topography) or, in other words, horizons may cross the terrain.

These modeling constraints are important since they give the modeler a sense of order in the modeling process and, more importantly, allows the modeler to constantly supervise if any surface intersection occur. In addition, the considered surface intersection constraints provide a sense of control whenever the user changes a surface. Furthermore, they assure geomodeling expeditiousness since, if no constraints were considered, then whenever a surface was modified, other surfaces would not be affected by this edit and had to be manually edited. This would be very time consuming and would negatively affect geomodeling efficiency. Note that this workflow is different from the one presented by (Caumon et al., 2009) since the authors consider fault modeling first and end with horizon modeling. In this paper, faults, unconformities (e.g. erosion) or intrusion are not considered.

3.4. Sketching of terrains and sub-surface layers

Layer-cake structures are encoded as a set of heightmaps, which are a common surface representation for horizons and terrains (Natali et al., 2013). A heightmap is an explicit surface formalized as $h: [x_1, x_2] \times [y_1, y_2] \in \mathbb{R}^2 \to \mathbb{R}$. Since 3D content is produced inside a proxy box, each point of a heightmap is contained within a set $B = [x_1, x_2] \times [y_1, y_2] \times [z_1, z_2]$, $B \in \mathbb{R}^3$. Each 3D modeling interaction, either spatial or touch gestures, have a corresponding geometric transformation associated to modify a heightmap, namely, the geomodeling operations described in (Table 1) and illustrated in (Figs. 5 and 6).

By sketching in mid-air, the position of the drawing device is used to define a set of point cloud curves that can be used in two ways. Based on Thin Plate Spline interpolation (TPS), a heightmap can be interpolated to the sketched points (Fig. 5(a)). This technique allows the user to generate the global features of a horizon or terrain, and is commonly used for terrain reconstruction (Bærentzen et al., 2012). Alternatively, the sketched points can be used to locally adjust an image mask or brush (Gonzalez et al., 2003). For instance, if the image mask is a Gaussian function, then the peak of the function can match the point's height (Fig. 5(b)). This modeling feature is especially useful if the user wishes to add a set of depressions or elevations, such as a mountain range.

Table 1
Type of interaction and corresponding geomodeling operation that affect the surfaces either globally or locally.

Interaction	Geomodeling operation	Surface model	Global or local features
Spatial	Point cloud curve for surface fitting	Thin plate spline	Global
Spatial	Point cloud curve for surface editing	Image mask	Local
Spatial	Surface editing	Image mask	Local
Touch	Surface editing	Image mask	Local
Touch	Surface height	Vertical translation	Global

Moreover, when continuously tracking the position and orientation of the drawing device, the user can also create local elevations or depressions in real-time, but in this case, the image mask can be rotated, thus, adding a new degree of modeling freedom to the workflow. Here, the height of the drawing device relative to the touch screen corresponds to the peak of the Gaussian function.

When modeling with touch gestures, image masks are also used to emulate both elevations and depressions, where it is possible to introduce multiple surface editions by touching the screen at several points (Fig. 6). Also, through touch interaction, it is possible to change the heights of the horizons and terrain, thus, altering the layer thickness. The heights can be adjusted by using the slider bar (Fig. 8), where each heightmap has a color coded label that can be slid up or down altering its vertical height.

Local features are modeled by introducing elevations or depressions through the use of an image mask. A proper image mask for geomodeling of heightmaps is the Gaussian function or, more generically, the elliptical Gaussian function (Fig. 7(a)):

$$g(x, y) = A \exp\left(-\frac{1}{2}\left(\left(\frac{x - x_0}{\sigma_x}\right)^{y} + \left(\frac{y - y_0}{\sigma_y}\right)^{y}\right)\right) \tag{1}$$

where A is the amplitude; x_0 and y_0 the center; σ_x and σ_y is the variance along x and y, respectively; $\gamma \geq 1$, the exponent that gives to the elliptical Gaussian a more circular ($\gamma \approx 2$) or square ($\gamma > 2$) shape. Note that the Gaussian surface is a particular case of (Eq. 1) when $\sigma_x = \sigma_y = \gamma = 1$. Individually, this mathematical function resembles a mountain or valley. When adding various different and contiguous Gaussians, the shape of a geological object comes to shape.

3.5. Affine transformations

The modeling process demands the visualization of the 3D content under many different angles. In order to visualize the modeled content, several affine transformations must be applied to the camera with easy-to-use multi-touch gestures (Kim et al., 2006). A total of 5 degrees of freedom are available, namely, two translations for displacing the proxy throughout the *xOz* plane, two rotations along the normal and tangential directions of the proxy's bottom plane, and a uniform scale. These transformations are performed by using the following set of interactions (Fig. 9): (i) pan gesture for translation; (ii) pinch open and pinch close gestures to zoom in and out, respectively, or with two fingers press and move them to each other or away along a straight line to zoom in or out; and (iii) rotate gesture for rotating the proxy box around an axis that crosses vertically its centroid.

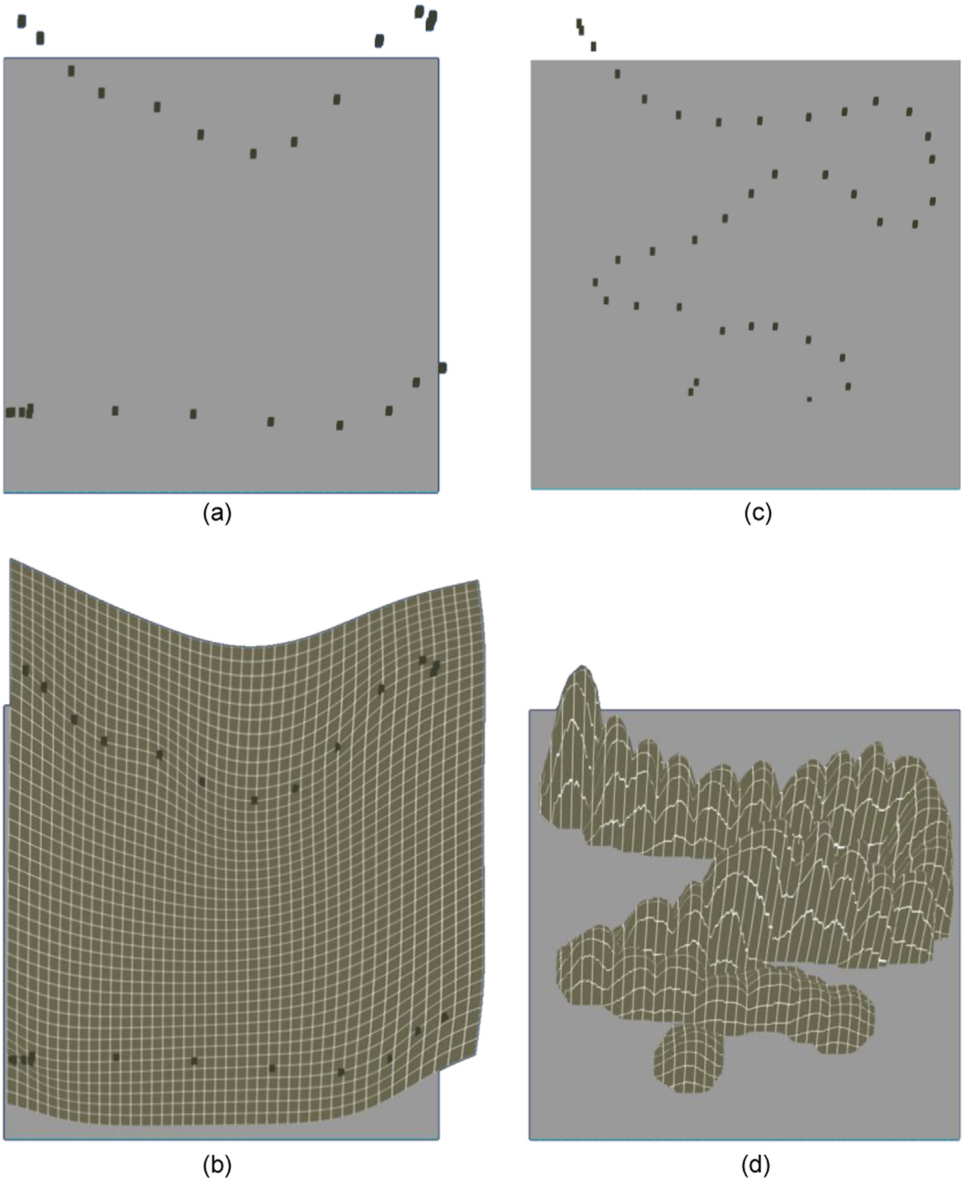


Fig. 5. Spatial interactions used for geomodeling: (a,b) point cloud and surface fitting with TPS; and (c,d) point cloud and local adjustment of image mask functions.

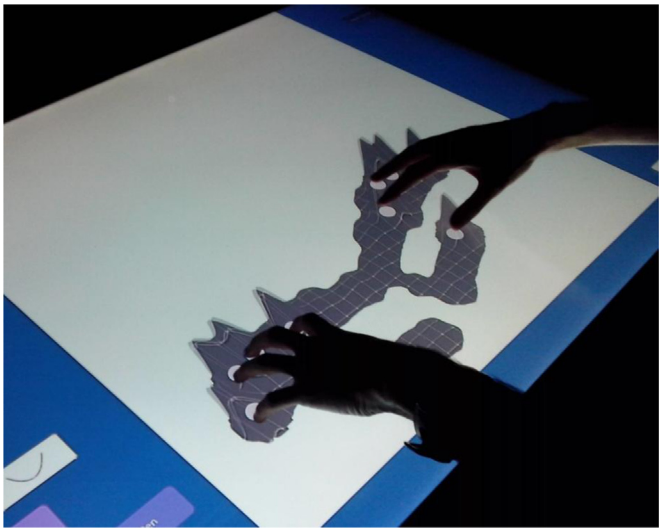


Fig. 6. Touch interactions used for geomodeling.

3.6. *Clipping*

Exploring the interior of a layered structure is a necessary task to reveal the amount of volumetric information contained within. Therefore, clipping planes were implemented to move along the horizontal canonical axes of the proxy box so that the user can visualize a specific part of the model (Fig. 10). Graphically, the clipping planes can be evoked by touching and dragging any of the four handles placed at the bottom corners of the proxy.

The user may place clipping planes at a desired location and a detailed view of the layer borders will appear on the clipping plane (Fig. 10). This functionality allows the modeler to observe the different layers within the proxy volume and edit them afterwards through interactive sketching.

4. User study

To conduct the usability study, the application called GeoIllustrator (Lidal, 2013) was used as the WIMP system. As with

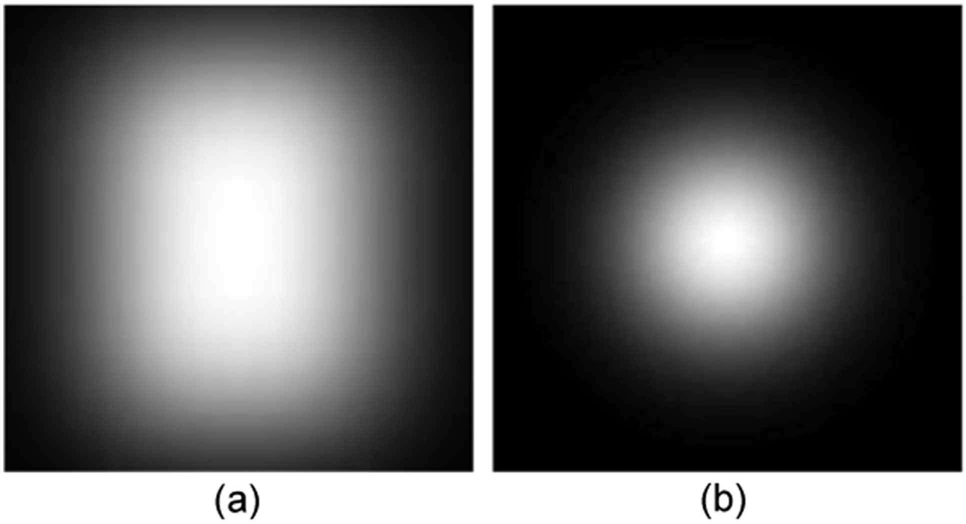


Fig. 7. Image masks or brushes used for representing elevations and depressions of a heightmap: (a) spatial interaction (elliptic super-Gaussian); and (b) tap and/or drag (circular Gaussian).

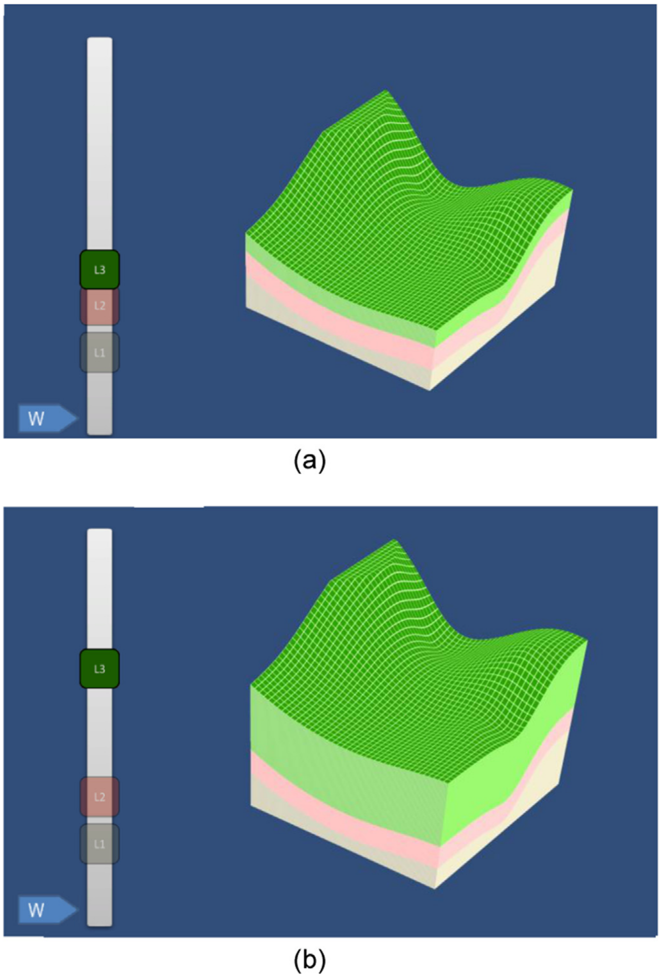


Fig. 8. A slider bar allows changing the global height of the surface layers. (For interpretation of the references to color in this figure, the reader is referred to the web version of this article.)

GeoCake, the GeoIllustrator application also relies on sketches to produce 3D content. GeoIllustrator presents some interaction differences, namely, it uses mouse and keyboard as input devices for modeling and navigation tasks. In addition, GeoIllustrator only permits 3D sketches that belong to a plane, either on the proxy faces or an arbitrary plane inside the proxy box. GeoIllustrator counts on a surface fitting algorithm to interpolate the sketched curves, in this case, Variational Hermite Radial Basis Functions method is used (Brazil et al., 2010; Lidal, 2013). Despite these differences, GeoIllustrator is a great control example for the comparison study because it sets the user into a conventional interaction approach: GeoIllustrator was tested on a PC using the mouse and keyboard, and the user was seated. On the other hand, user tests with GeoCake were conducted with the spatial interaction system described in Section 3.1.

A total of 15 users with ages between 22 and 47 years (29.3 ± 8.11 years old) were asked to sketch several geo-objects. All users had at least a bachelor's degree. Only one did not possess a multi-touch device (e.g., tablet or smartphone) and 80% of the tested users do interact with a multi-touch device several times per day. All users have experienced 3D display devices (e.g., 3D movies or IMAX), but none ever experienced custom view made from precise head tracking, and 87% have used spatial interaction devices (e.g., Microsoft Kinect). The test sessions were individual and each task was timed. The expected duration of a test session was about 60 minutes and was divided in two phases. During each phase, either GeoCake or GeoIllustrator was tested and the user performed three geomodeling tasks as described in the next section.

Before starting a test, it was necessary to draw which system a user would test first, although the number of users per initial system was as balanced as possible. Note that this is a temptative form to prevent biased results. Then, at the beginning of each phase, a short system presentation was made in order to explain how each objectified functionality worked. Afterwards, the user would test the systems up to 5 minutes to achieve habituation. Finally, the users were asked to complete a questionnaire regarding the system and about the tasks undertaken in order to classify the level of difficulty felt during their tasks performance and on the use of the available features.

4.1. *Geomodeling tasks*

We asked users to complete three geomeodeling tasks using both GeoCake and GeoIllustrator (Fig. 11). The first task consisted in illustrating a simple terrain with a wide canal that crossed through the middle of the surface, which should be filled with water. The second task focused on exploiting the addition of details. For this purpose, an example illustration of a layer-cake model with several elevations and depressions was shown to the

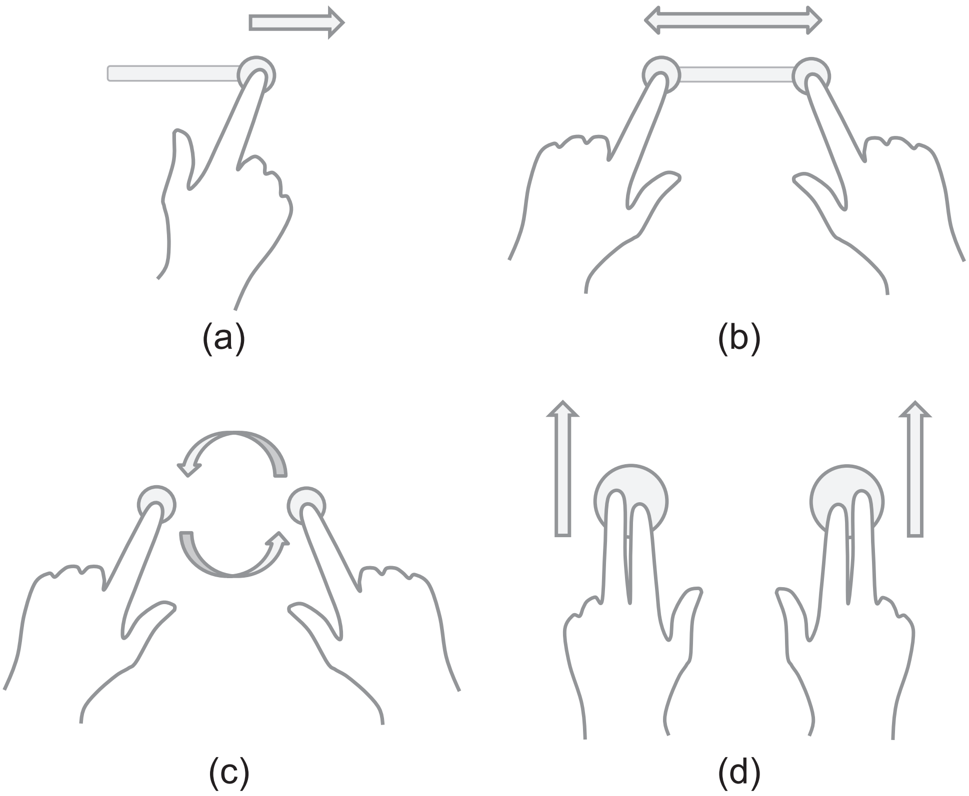


Fig. 9. How affine transformations are applied to the 3D geological content: (a) one tap and drag for translation; (b) pinching or press and drag with two fingers for uniform scale; (c) two tap and press and revolve for vertical rotation; and (d) multi-touch drag for horizontal rotation.

users so that they could create a similar scenario, but not necessarily a copycat illustration. Finally, in the third task, users were requested to illustrate a scenario with three similar stratigraphic layers. The scenario consisted of a mountain top surrounded by water, where the shape of the layer-cake was similar to a rectangular slice.

5. Results and discussion

Both systems produce illustrations of layer-based models built of multiple horizontal oriented surfaces. These models are initial concepts of a terrain or layer-cake structure and do not present intricate geological details. Due to their simplicity, such models are ideal for expedite modeling with a spatial and sketch-based interfaces as they share similarities with terrain modeling in game engine environments [Unity3D,[9] Blender[10]].

Evaluation times of the corresponding geomodeling task are presented in the graph of Fig. 12. To get a more quantitative feeling, a statistical analysis was run by applying the Wilcoxon signed-rank test to the execution times (Wilcoxon, 1945). This statistical test performs a pairwise comparison between two sets of scores, which come from the same participants, to assess whether their means or medians differ. From these statistical tests, it is possible to infer several advantages of a spatial interface for geomodeling. In particular, GeoCake presents significantly better results in task 2 ($Z=-2.954$, $p=0.003$). However, both evaluated systems presented timings without statistically significant differences in tasks 1 and 3 ($p>0.05$).

In particular, the execution time was slightly longer in task 1 when using GeoCake. This can be explained by the fact that GeoCake allows the user two distinct possibilities to model smooth surfaces, namely, local edition with an image mask or global edition using the TPS surface fitting algorithm. During task 1, it was noticed that some users opted to locally edit the surface with an image mask throughout the entire proxy box, which is a less expedite option compared to the global surface fitting procedure which rapidly generates the whole terrain from just a few point cloud curves.

Table 2 gives a qualitative point of view of the results obtained through user study questionnaires, which were also subject to the Wilcoxon signed-rank test. When confronted with the performed illustrations, participants strongly agreed that GeoCake had the best results for Task 2 ($Z=-3.355$, $p=.001$), and was not significantly worse than GeoIllustrator in Tasks 1 and 3, thus, reinforcing the quantitative results. Participants found GeoCake tailor made to add several details, as the multitouch screen offered a more natural way to add several local elevations or depressions at a time when compared to using a pointer device.

Regarding stroke production, participants strongly agreed that creating point cloud curves was easier in GeoCake ($Z=-3.244$, $p=.001$), because it does not restrict the user to sketch curves on planes (proxy faces or arbitrary planes) as demanded with GeoIllustrator.

Participants also reported that adding details to a surface using GeoIllustrator had very unexpected results. This may be justified by the surface fitting algorithm that GeoIllustrator uses: the Variational Hermite Radial Basis Function method, which is too complex to deal with simple point cloud curves, since radial basis function algorithms finds better applications for large point cloud data sets (Carr et al., 2001). As for the surface fitting methods the TPS representation was chosen as it presents great performance

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[9] unity3d.com/

[10] https://www.blender.org/

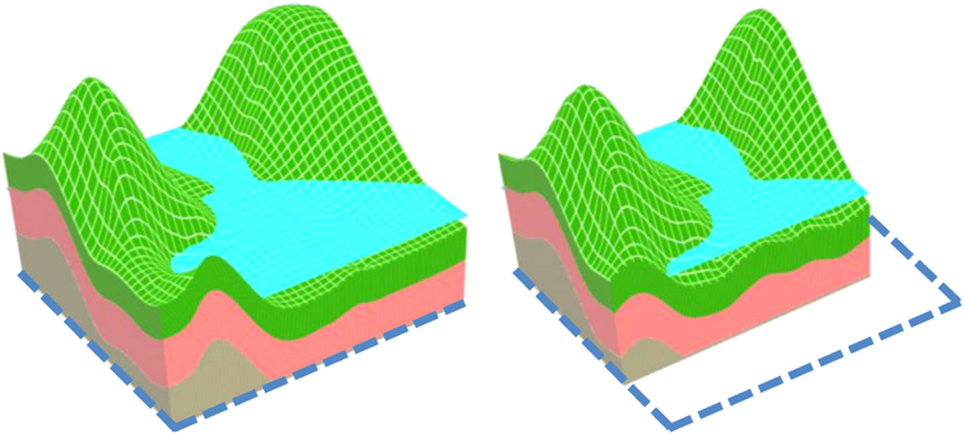
original model
clipped model

Fig. 10. Clipping of the proxy box to explore the interior of the layered structure.

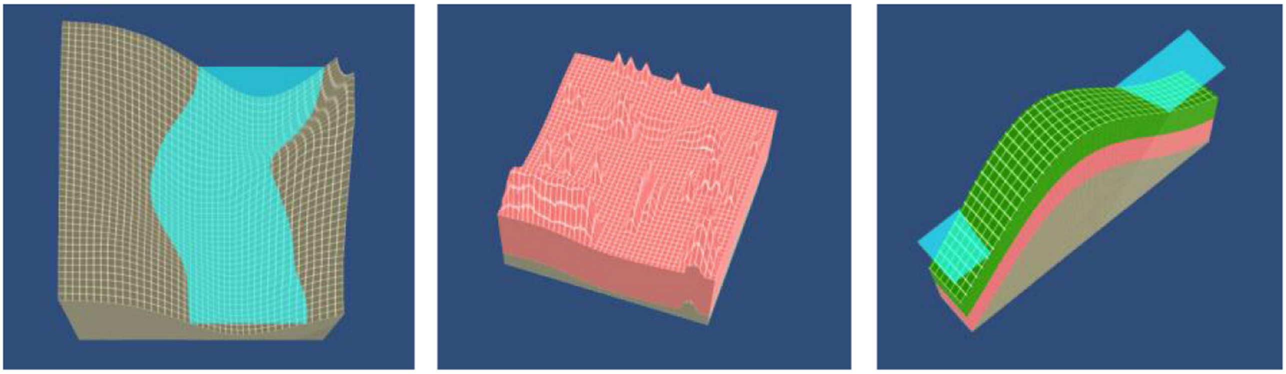
task 1 model
task 2 model
task 3 model

Fig. 11. Geological models used in the user study.

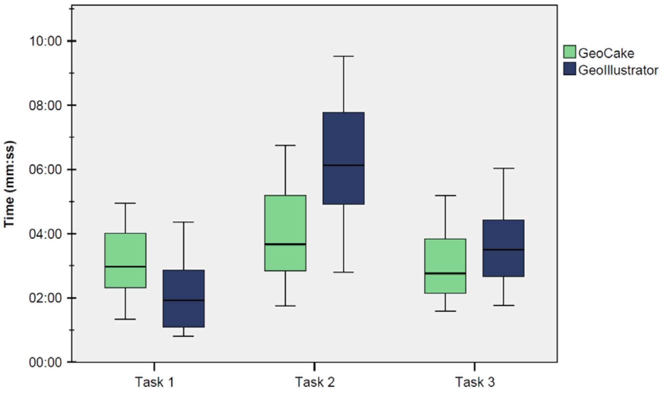

Fig. 12. Evaluation times of the geomodeling tasks using GeoCake and GeoIllustrator.

Table 2
Participants preferences regarding different criteria for the evaluated systems: Median (inter-quartile range).

How easy was it to …	GeoCake	GeoIllustrator
generally use the system?*	3 (1)	2 (1)
perform task 1?	3 (2)	4 (1)
perform task 2?*	3 (1)	1 (0.5)
perform task 3?	4 (1)	3 (2)
create surfaces using point cloud curves?*	3 (1)	2 (1)
translate the model?	4 (1)	4 (1.5)
scale the model?*	4 (1)	3 (1.5)
rotate the model?	4 (1.75)	4 (1)

* Indicates statistical significance.

for the relatively small amount of outlined points, thus enables a real-time surface fit. TPS also guarantees that the surface goes through all the points. This is important as TPS shows a predictable behavior from the modeler's point of view.

To explore the modeled content, both systems offer similar transformations. Users can translate the model to a more suitable place, and scale it to either get a better overall view or to give a closer look at a specific detail. It is also possible to rotate the model, either through vertical or horizontal axis, to achieve the desired perspective upon the created terrain. Concerning model exploration, both systems offered very similar experiences to participants, which show that GeoCakes's approach, albeit less familiar, is at least at par with a very common mouse-based interaction. Moreover, when scaling the model, participants strongly agreed that GeoCake's multi-touch approach was easier than the one used in GeoIllustrator ($Z=-2.310$, $p=0.021$).

Finally, when asked about the general level of difficulty, participants strongly agreed that GeoCake was easier to use ($Z=-2.972$, $p=0.003$). This demonstrates that a spatial interaction system brings several advantages for 3D geomodeling, namely, expedite sketching throughout the entire proxy box and fast addition of details through a multi-touch screen.

All users reported that the spatial interactive system allows to create layered structures in a fast and simple way, and that hand gestures are suitable to define the gross content of the surfaces while touch gestures are great add local details. Users rapidly understood how to interact with the spatial interaction system as they easily completed each task, without never having used the spatial interaction system before. The presented usability study indicates that the developed spatial system is, indeed, a viable alternative to systems that incorporate a conventional WIMP interaction (Lidal, 2013: Bendiksen, 2013).

6. Conclusion and future work

This work explores the existing gap in geomodeling with spatial interactive systems. The main contribution of this work consist of exploring the potential and examines the feasibility of spatial user interfaces for illustrating geological structures, namely, terrains and layer-cake structures. Users are allowed to work in a semi-virtual 3D space, where they can use hand positions and touch gestures as inputs for geometric modeling functions. Head positions are tracked to provide (an almost holographic) 3D visualization of the produced content. In other words, the proposed system provides capabilities that augment both modeling and visualization functions by using a limited number of 3D input and touch gestures, allowing a direct and expeditious interaction to rapidly externalize initial concepts when compared to the conventional use of mouse and keyboard.

As future work, it is necessary to cope with GeoCake's current geomodeling limitations in order to become a more interesting tool for geologists. In particular, the following functionalities would improve expeditiousness and produce more meaningful models, namely, (i) simultaneous layer edition, where users could locally or globally elevate or depress a series of layer in a consistent manner while maintaining their relative position; (ii) sketching of other geology features such as faults, unconformities or intrusion.

Through a usability study we compared the proposed spatial interaction system with a conventional WIMP system. The results show that through spatial interaction, users performed geomodeling tasks in a shorter time interval. The main conclusion is that hand gestures indeed can be an effective sketch-based input for modeling heightmaps, in general, and geological layer data, in particular. Additionally, the study demonstrates that simple geological models can be successfully modeled with the proposed sketch system in both a natural and simple fashion.

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Appendix A. Supplementary material

Supplementary data associated with this article can be found in the online version at http://dx.doi.org/10.1016/j.cageo.2016.02.009.

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