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Supporting Focus and Context Awareness in 3D Modelling Tasks Using Multi-Layered Displays

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Abstract

Most 3D modelling software have been developed for conventional 2D displays, and as such, lack support for true depth perception. This contributes to making polygonal 3D modelling tasks challenging, particularly when models are complex and consist of a large number of overlapping components (e.g. vertices, edges) and objects (i.e. parts). Research has shown that users of 3D modelling software often encounter a range of difficulties, which collectively can be defined as focus and context awareness problems. These include maintaining position and orientation awarenesses, as well as recognizing distance between individual components and objects in 3D spaces. In this paper, we present five visualization and interaction techniques we have developed for multi-layered displays, to better support focus and context awareness in 3D modelling tasks. The results of a user study we conducted shows that three of these five techniques improve users' 3D modelling task performance.

Keywords: ploygonal modeling, modeling, modling interfaces, modeling, information visualization, visualization

ACM CCS: I.3.6 [Computer Graphics]: Methodology and Techniques---Interaction techniques H.1.2 [Information Systems]: User/Machine Systems---Human factors

1. Introduction

Modern computer games and movie industries, as well as others, require creation of highly complex and ever more realistic 3D models. There are a range of modelling software currently available (e.g. 3ds Max [Aut14], Maya [Aut14], Blender [Ble14]), which provide various tools for creating, editing and rendering 3D polygonal models. The 3D modelling processes supported by these software include tasks such as selection of one or more basic components (e.g. vertices, edges, faces) or objects (parts of a model, e.g. door of a 3D car model), manipulation and transformation of objects, addition or removal of surfaces and texturing of surfaces.

Existing 3D modelling software have generally been developed for conventional 2D displays. This requires projecting the 3D modelling world on to one or more 2D viewports, to provide perspective or orthogonal views of the virtual 3D world. Most 3D modelling tasks require the use of multiple viewports (each with a different view) to give the user sufficient visual information about their modelling tasks.

Some 3D modelling tasks (e.g. vertex or edge manipulation) require modellers to have a detailed view of the components they are working on. We define this type of view as the 'focus'. Some other tasks such as object transformation, on the other hand, require an overview of the entire 3D modelling space, or at least a large part of it. This type of view can be defined as the 'context'. In reality, many modelling tasks require the modeller to not only view and 'focus' on the components they are working on, but also be 'aware' of the larger 'context' in which those components exist. It is therefore crucial to better understand the issues related to focus and context awareness in 3D modelling tasks, and provide effective visualization and interaction techniques to support such tasks in 3D modelling software.

In this paper we present five visualization and interaction techniques we have developed for multi-layered displays (MLDs) to allow modellers to isolate, slice and view 3D models, with the aim of improving their ability to work on parts of a model in detailed mode, while remaining aware of the context in which those parts exist in the entire model. We also describe a user study we have conducted to evaluate the effectiveness of these techniques in comparison to tools provided by conventional 3D modelling software designed for 2D displays.

The paper starts with a review of related research on focus and context visualization techniques (Section 2), followed by a summary of two studies we have previously conducted to better understand problems related to focus and context awareness in 3D modelling tasks (Section 3). We then present our proposed focus and context awareness visualization and interaction techniques (Section 4) along with the user study conducted to evaluate them (Section 5), as well as a few potential improvements that could be made (Section 5.6) and some conclusions (Section 6).

2. Related Work

Although there is not much research dealing specifically with focus and context awareness in 3D modelling tasks, there is extensive research dealing with issues related to visualization of focus and context information in 2D environments. In their review of this literature, Cockburn *et al.* [CKB08] divide focus and context visualization techniques into four categories: *overview + detail*, *zooming*, *focus + context* and *cue-based*.

Overview + detail techniques use separate spatial areas to present an overview of the entire information space along with a detailed view of parts of it. Overview+detail is supported by 3D modelling software that provide multiple viewports. However, due to the spatial separation of the overview and detail spaces, the use of overview+detail techniques can require more mental effort, and they can be slower to use than other visualizations relying on a single view [HBP02].

Zoom-based techniques are also commonly used in 3D modelling software, and are often combined with overview through the use of multiple viewports. Although studies of the effectiveness of zooming in 2D settings have been inconclusive, there is some evidence for their benefits [HBP02].

While these two types of techniques, either separate focus and context views spatially (overview+detail) or temporally (zooming), *focus + context* techniques combine focus and context into a single view, and by doing so, they reduce viewer's reliance on short-term memory which is required for assimilating views separated spatially or temporally [CKB08]. Most focus+context techniques are distortion based, using change of scale to combine focus and context areas (for reviews see [LA94, PA08]). As such, they are not generally suitable for 3D modelling tasks where presentation of spatial relationships (e.g. distance), and the ability to find and select targets are important.

The focus+context techniques that are not distortion based, often use alpha-blending [PD84] to combine two or more layers with different levels of transparency. The cutaway technique, for instance, is used in volumetric medical data visualization [VKG05]. There are a range of interactive cutaway techniques that allow cutting manually based on a location specified by the user [BSM*02], or automatically around the object of interest [DWE03] or using the hierarchy of the objects of a model [LRA*07]. However, all cutaway techniques remove parts of the rendered image, and therefore, reduce contextual information [MPDSF11]. Other techniques have been developed to address this problem in rendered volumetric data. For example, ClearView [KSW06] provides explicit ordered layers, hybrid visibility [BRV*10] allows generating 3D illustrations using 2- and 3D layers, importance-aware composition [MPDSF11] supports manual layering based on importance and deformation-based techniques [MTB03] distort the context in which the area of focus is shown (for a review see [KSW06, BRV*10]). However, all such focus+context techniques are applied at the pixel or voxel level to render several layers into a single-layer rendered view. As such, they cannot be used in 3D modelling environments, which require the user to interact with components and objects of a 3D model, rather than a series of pixels or voxels of a rendered image. Furthermore, Baudish and Gutwin [BG04] have identified that viewers of information being displayed on a single layer generated using alpha-blending type techniques often have difficulty in identifying the actual location of the information on different layers. This type of visual ambiguity can be problematic in cases such as 3D modelling tasks, which for instance require accurate identification and precise selection of often small and overlapping components.

Unlike overview+detail, zooming, and focus+context, which all define the area of focus as a sub-space of the context, *cue-based* techniques define focus based on some non-spatial properties [CKB08], and display these in a manner that separates them from the context. Most 3D modelling software allow users to group together objects or components of a 3D model, which can then subsequently be selected to hide or show them. This process of hiding grouped objects can, however, lead to loss of contextual information.

Furthermore, all these software-based focus and context awareness techniques, rely on the use of 2D displays, which have a major disadvantage in their lack of support for depth perception [War12]. In the absence of important depth cues that human vision heavily relies on (e.g. motion parallax [GGSF59]), it becomes difficult for users to understand the relationships and distances between objects in a virtual 3D world when viewed on 2D displays [WPRC02, HMW06].

Alternatives to 2D displays, including volumetric, lenticular, stereoscopic, immersive and head-mounted displays, have mainly been used for viewing 3D spaces and not 3D modelling. One alternative with potential use for 3D modelling is a dual-layered display [Pur14], called MLD. MLD comprises two physically separated (around 1cm) front and back LCD layers, where the transparency of the front layer can be adjusted to allow viewing of the back layer. This physical separation and transparency of the two layers not only enables the contents of the two layers to be viewed simultaneously, but also creates a sense of depth perspective between the images viewed on the two layers, particularly through motion parallax [PRW06]. Wong *et al.* [WWJM*05] point out that MLD allows users to switch their attention between the content presented at different depth planes within the same visual field of view. We have previously shown that this can be used to support focus and context awareness in 2D applications [MMRW04].

3. Focus and Context Awareness in 3D Modelling Tasks

As focus and context awareness in 3D modelling tasks had not been studied previously, we conducted two studies to investigate the kinds of challenges 3D modellers face when performing their modelling tasks. Although a full discussion of these studies is beyond the scope of this paper, we provide an overview of them here (for further details, see [MMR14]).

The first study involved 25 students who answered a questionnaire after completing their 3D modelling course work, which required creating a fully textured and skinned character over several weeks using the Blender 3D modelling software. In the second study we observed and interviewed 13 professional 3D modellers, each with 2 to 11 years of experience working with different modelling software. These semi-structured interviews sought responses to 46 open-ended questions. Some of these questions aimed to identify modelling tasks that were time consuming or problematic. There were also five specific focus and context awareness tasks where interviewees were asked to explain whether they faced any difficulties in carrying them out. These two studies identified a range of common focus and context awareness problems faced by both novice and professional modellers. These can be categorized as:

- Maintaining position and orientation awareness.
- Identifying and selecting objects or components.
- Recognizing distances between objects or components.
- Realizing relative positions of objects or components.

Our studies showed that these difficulties are not only caused by the complexity of the models being created but also by the ineffectiveness of existing software tools, and the 2D display technology they rely on, in helping 3D modellers to maintain their focus and context awareness while performing modelling tasks. Modellers try to cope with their challenging modelling tasks by using techniques such as opening multiple viewports, changing focus between viewports, zooming in/out, hiding parts of their models, rotating and moving around their models and so on. The use of such techniques however is not always sufficient to provide enough focus and context awareness in 3D modelling tasks.

4. Focus and Context Awareness Techniques

Five focus and context awareness techniques were developed to deal with the four groups of problems identified through our user studies. These five techniques utilize the two layers of an MLD to display different types of focus and context awareness information. Even though focus and context information can be displayed on either the front or back layer, or interchangeably between them, it was decided to use the front layer of MLD to display information related to the objects or components of interest (i.e. focus) and the back layer to display information related to the context. The five focus and context awareness techniques that were developed for MLD are: *Object Isolation*, *Component Segregation*, *Peeling Focus*, *Peeling Focus and Context* and *Slicing*.

4.1. Object isolation

Object isolation is a technique for separating the object(s) of interest from the rest of the model. It is intended to be used when modellers need to shape an object which is overlapping with other objects within a model. For example, in a 3D human model, an internal object such as the heart is usually behind other objects such as the longs, ribs, and as such, shaping it with all the other objects around it can be difficult. In such a case, object isolation can be used to separate the heart from the rest of the model.

The object isolation technique works by presenting the selected object on the front layer while the non-selected objects are displayed on the back layer of MLD. By separating objects into two layers, modellers can perform tasks on the object of interest in a less crowded environment, while the transparency of the front layer permits the overall context of the model relevant to the task being performed to be seen. In this technique the same panning and zooming effects are applied to both layers.

Figure 1 shows the initial view of a 3D car model, where the body of the car and its internal parts are visible to the viewer. The objects shown on the back layer are in wireframe mode (Figure 1a) with edges coloured in blue, and the objects on the front layer are displayed in solid mode (Figure 1b). It is important to note here that in this paper we will use screen shots to illustrate how a model is displayed on MLD using its two layers. In most cases, the screen shots will consist of three images. The left and middle images will show the separate back and front layers of MLD, respectively, while the right image will show the combined two layers as seen on MLD. Although images of the combined MLD layers shown here look like flattened alpha-blended images, on an actual MLD the layers are separate and support some depth perception (e.g. through motion parallax).

Figure 2 shows how the selection of the steering wheel set in object isolation mode moves it to the front layer of MLD (Figure 2b), thus allowing it to be manipulated and changed independently, while remaining in the context of the rest of the model shown on the back layer (Figure 2a).

4.2. Component segregation

The component segregation technique is similar to object isolation, but allows manipulation of the model at the component level. Component segregation splits the components of a selected object between the two layers. Components that are closer to the viewer are shown on the front layer, while the components that are on the far side of the selected object are displayed on the back layer. The location of the mouse cursor, either on the front or back layer, determines which components can be manipulated. This eliminates the possibility of selecting components on the wrong side of the object. The physical separation between the components of the front and back layers allows users to select the targeted components more accurately without having to hide other components, or perform any navigation which might change the model's orientation. Even though various components of a selected object are separated onto different layers, the transparency of the front layer of MLD makes all the components visible to viewer. Also, small head movements by the viewer allow motion parallax, and can improve visibility.

Figure 3 shows the component segregation technique being used to allow separating the components near to the viewer to the front layer of MLD (Figure 3b), while keeping the component further away from the viewer on the back layer (Figure 3a). Note that although a side view of the model is provided in this figure for ease of viewing, the component segregation technique is dynamically applied as the model is rotated and viewed from different positions

Figure 1: *The initial view of the 3D model of a car on MLD, showing the back layer (a), front layer (b) and combined view (c).*

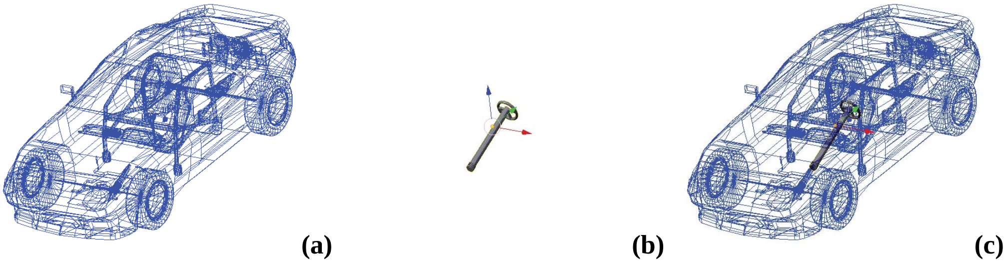


Figure 2: *Using the object isolation technique, the object of interest can be edited on the front layer (b) while context of the rest of the model is shown on the back layer (a).*

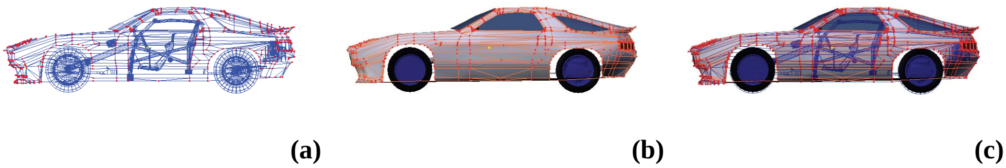


Figure 3: *Using the component segregation technique (c), the components of interest can be edited on the front layer (b) while context of the rest of the model is shown on the back layer (a), or vice versa.*

(see Section 4.6 for details). Also note that in Figure 3 the body of the car is selected and the model is in component editing mode. At this stage, the edges and vertices that are closer to the viewer are shown in red on the front layer, while the components on the other side of the model are shown with blue edges and red vertices on the back layer. Although this makes it possible to directly compare and manipulate components on either side of the car, these components are not directly overlapping on MLD, as would be the case on a single-layer display.

4.3. Peeling focus

Peeling focus aims to assist modellers with two types of tasks: finding objects of interest when they are hidden or occluded by other objects, and realizing the relative position of objects in a model. When peeling focus is used, portions of the model on the front layer are incrementally removed (or shown, under user's control), while the context of the model shown on the back layer remains the same. This technique enables the viewer to expose objects of interest on the front layer, by moving a clipping plane towards or away from them to incrementally expose what is previously hidden or occluded by objects nearer to the viewer.

Figure 4 demonstrates the results of using the peeling focus, as seen on MLD with both layers combined. Figure 4 (left) shows the initial view of the model. When peeling focus is applied, a portion of the model closer to the viewer and in the path of the *Z*-axis is incrementally removed from (or added to) the front layer. This process steadily exposes interior objects, as illustrated in Figure 4 (middle and right), allowing the viewer to locate the objects of interest inside the model. Even though peeling focus removes portions of the model shown on the front layer, the viewer can still maintain awareness of the overview of the model on the back layer.

It should be noted that the portion of the model which is peeled on the front layer is determined by the orientation of the model with respect to a clipping plane (see Section 4.6 for details). Therefore any changes to the orientation of the model will alter the visibility of the model and the segments being peeled. For example in Figure 5,

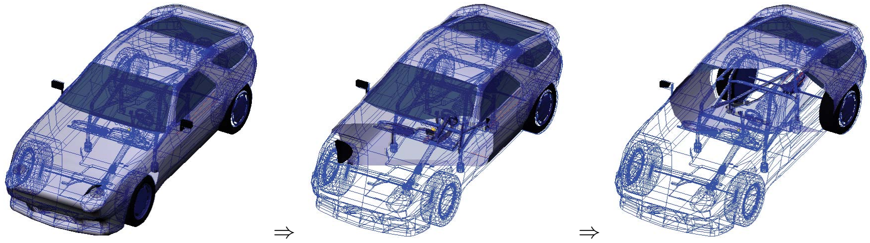
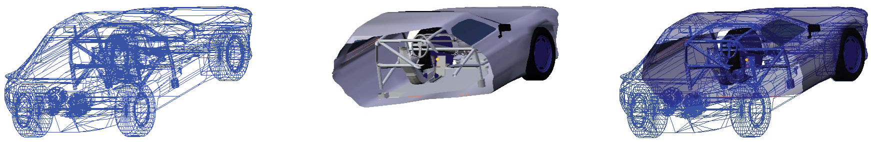


Figure 4: *As the peeling focus technique is interactively applied, it peels the content of the front layer (shown left to right).*



(a) (b) (c)

Figure 5: *The peeling focus technique is dynamically applied as the viewing position changes.*

a different segment of the model is shown on the front layer because the model has been rotated. The orientation of the overview (i.e. context) shown on the back layer has also changed accordingly.

4.4. Peeling focus and context

Unlike peeling focus, which only removes parts of the model from the front layer, the peeling focus and context technique removes parts of the model from both layers (i.e. both the focus and context layers). Figure 6 demonstrates the initial stage of the process of peeling focus and context, where a portion of the model is removed from both layers. Figure 7 show further peeling of focus and context. Once again, it should be noted that as with the previous technique, parts of the model that are peeled change interactively depending on the orientation of the model to a set of clipping planes (see Section 4.6 for details).

4.5. Slicing

The slicing technique removes parts of the model from the back layer and shows them on the front layer. The parts that appear on the front layer are displayed in solid mode while the rest of the model on the back layer remains in wireframe. To demonstrate the slicing technique, let's assume that the view of the model being displayed on MLD is that shown in Figure 8(c), where all the objects of the model are shown in wireframe mode on the back layer (Figure 8 a), and in solid mode on the front layer (Figure 8 b). The initial application of the slicing technique will change the view to that shown in Figure 9(c), where objects shown on the front layer are removed completely (see Figure 9 b is blank), and what is shown to the viewer is the model of the entire car in the wireframe mode on the back layer (Figure 9 a). When the slicing technique is then applied, it incrementally removes portions of the model from the back layer and moves them to the front layer, as shown in Figure 10. As further slicing is performed, subsequent portions of the model are affected. The front portion of the sliced part of the model shown on the front layer is eventually removed as slicing continues through the model (Figure 11). As with the previous two techniques, the portions of the model that are sliced dynamically change, depending on the orientation of the model to the near and far clipping planes which define the thickness of the slice (see Section 4.6 for details).

It should be noted that each of the five techniques presented here is designed to address a particular type of problems faced by modellers. The slicing, and peeling focus and context, techniques are different from the other three techniques in that they do not preserve the visibility of the entire model in the context layer at all times. Therefore, these two techniques are more suitable for cases where the modelling tasks being performed do not require modellers to refer to the entire model, for instance when the focus and context do not necessarily involve different parts of the model (e.g. different objects) but may be of a single object where context can be the rest of the same object.

4.6. Implementation

We implemented our techniques in the open source Blender 3D modelling software, using the OpenGL graphics library in C++. A standard PC with a dual output graphics card was used, where each of the display outputs was connected to one of the two video ports of the MLD (one for each layer).

In component segregation method, the visibility of the surfaces to appear, either on the front or back layer, is determined by calculating the normal values of polygon using their dot products. The two vectors required in the dot product calculation are determined by three connected vertices of each polygon in the clockwise rotation.

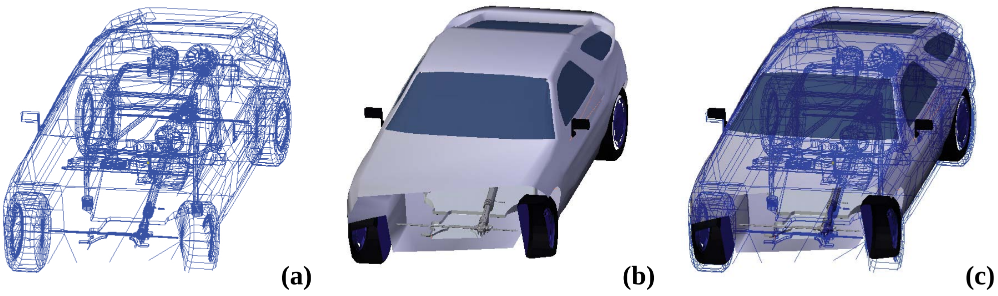


Figure 6: *The peeling focus and context technique removes parts of the model from both back (a) and front (b) layers of MLD.*

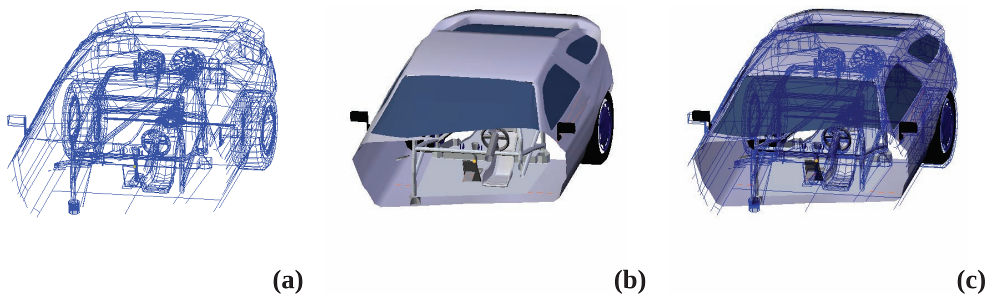


Figure 7: *Further use of the peeling focus and context technique removes parts of the model from both layers of MLD.*

Figure 8: *View of the model on MLD before the slicing technique is applied, back layer (a), front layer (b) and the combined view (c).*

For vertices: $\mathbf{v_1} = (x_1, y_1, z_1)$, $\mathbf{v_2} = (x_2, y_2, z_2)$, $\mathbf{v_3} = (x_3, y_3, z_3)$ we have:

$$\vec{\mathbf{a}} = (x_1 - x_2, y_1 - y_2, z_1 - z_2),$$

$$\vec{\mathbf{b}} = (x_3 - x_2, y_3 - y_2, z_3 - z_2),$$

where $\vec{\mathbf{a}}$ and $\vec{\mathbf{b}}$ can be rewritten as:

$$\vec{\mathbf{a}} = a_1\hat{\mathbf{i}} + a_2\hat{\mathbf{j}} + a_3\hat{\mathbf{k}},$$

$$\vec{\mathbf{b}} = b_1\hat{\mathbf{i}} + b_2\hat{\mathbf{j}} + b_3\hat{\mathbf{k}},$$

and the dot product of $\vec{\mathbf{a}}$ and $\vec{\mathbf{b}}$ is calculated as:

$$\vec{\mathbf{a}} \cdot \vec{\mathbf{b}} = a_1 b_1 + a_2 b_2 + a_3 b_3.$$

If the resulting $\vec{\mathbf{a}} \cdot \vec{\mathbf{b}} >= 0$ then the vertices $\mathbf{v_1}$, $\mathbf{v_2}$ and $\mathbf{v_3}$ belong to a polygon facing the viewer, and as such, must be displayed on the front layer of MLD, otherwise they are displayed on the back layer of MLD.

The peeling focus, peeling focus and context, and slicing techniques use two independent sets of clipping planes, one on each layer. However, the clipping planes work differently depending on the type of the technique being used. In peeling focus, and peeling focus and context, initially the depth assigned to the near and far clipping planes of both layers are set to 0.1 and 500, respectively. These represent the near and far planes in the viewing volume as set by the Blender software, thus guaranteeing the visibility of the entire model on both layers. In the peeling focus technique, only the near clipping plane of the front layer is moved, while the far clipping plane of the front layer and both clipping planes of the back layer remain stationary. In peeling focus and context, near clipping planes of both layers are moved together, while the far clipping planes of both layers remain stationary.

Figure 9: *Initial view of the model on MLD after the slicing technique is applied, back layer (a), front layer (b) and the combined view (c). Note that the front layer (b) is empty.*

Figure 10: *As the slicing technique is used, parts of the model between the near and far clipping planes are moved from the back layer (a) to the front layer (b) to provide the combined MLD view (c).*

Figure 11: *Further use of the slicing technique moves the slice shown on the front layer (b) back and forth across the model.*

In the slicing technique, three clipping planes are active at all times. On the front layer, the gap between the near and far clipping planes, which defines the thickness of the slicer, is set to three units. The gap of three units was selected based on some initial tests to provide a good view of the neighbourhood of the object of interest and context that is relevant to the tasks. When the slicing method is used, the depths assigned to the near and far clipping planes of the front layer are increased/decreased by 0.5, making the parts of the model contained between the two planes visible. On the back layer, however, near clipping plane is increased/decreased by 0.5, while the far clipping plane always remains stationary.

5. User Evaluation

We conducted an empirical study to compare the effectiveness of these five focus and context awareness techniques with several comparable techniques provided by existing 3D modelling software, which are: hiding, hidden surface removal, zooming and displaying models in wireframe mode.

The goal of this study was to identify whether there are any significant differences between the study participants' performance in completing their modelling tasks using the focus and context awareness techniques developed for MLD and the above-mentioned modelling techniques provided by conventional software for 2D displays. It is important to note that although there are also various 3D volume rendering and alpha-blending techniques available (see Section 2), the aim of our study was to compare our techniques against conventional interactive 3D modelling techniques commonly used by modellers.

5.1. Methodology

Two experimental conditions were used in this study, where participants were asked to perform a number of tasks using specific modelling techniques in each of the two environments: SLD (single-layer display) and MLD. SLD required using the unmodified Blender software with two side-by-side viewports on a conventional display, while MLD required using a modified version of Blender (which implemented the five techniques) on an MLD, with the context viewport on the back layer and the focus viewport on the front layer. The order of the use of SLD and MLD was counterbalanced to reduce possible learning effects across the two conditions.

The experiment aimed to answer the following questions:

1. Does the object isolation technique used with MLD improves focus and context awareness in comparison to using the hiding technique with SLD?
2. Does the component segregation technique used with MLD improve focus and context awareness in comparison to using the hidden surface removal technique with SLD?
3. Does the peeling focus technique used with MLD improve focus and context awareness in comparison to using the zooming technique with SLD?
4. Does the peeling focus and context technique used with MLD improve focus and context awareness in comparison to displaying the model in wireframe mode with SLD?
5. Does the slicing technique used with MLD improve focus and context awareness in comparison to using the hiding technique with SLD?

In SLD, two viewports of the same size were opened side-by-side. Different panning and zooming techniques could be used in the two viewports of SLD. Participants were also free to close the viewports at their own discretion. Although no specific tutorial was given to the participants prior to using SLD, they were given a sheet of paper containing a summary of various commands, such as short-cut keys and command buttons. Participants were also given an unlimited time to acquaint themselves with the features and functions of Blender.

In MLD, the focus and context were shown on two viewports, one on each layer of MLD. Unlike SLD, the same panning and zooming effects were applied to both focus and context viewports in MLD, as implemented in our five different techniques. Prior to using MLD, a tutorial was given to the participants to familiarize them with the five focus and context awareness techniques. There was no time limit for the tutorial session.

During the actual study tasks sessions, the participants were given several printed images of the models (of a 3D car) relevant to the tasks they were performing. These images included (1) the initial condition of the model, (2) a zoomed-in view of the object of interest (i.e. focus) that needed to be manipulated, (3) a zoomed-in view of other objects (i.e. context) relevant to the tasks and (4) the expected outcome (finished model) that needed to be produced. The participants were also given detailed instructions on the requirements of each task. These instructions explained the conditions that needed to be observed when manipulating the object of interest and the rest of the model.

5.2. Study tasks

Each participant performed 10 modelling tasks, five in each environment. The two sets of tasks and their level of difficulty were comparable, as confirmed by several experts who performed them prior to the experiment. The tasks were:

1. Increasing the size of a particular object under the constraint of other objects.
2. Matching the shapes of two objects on the opposite sides of the model.
3. Relocating an object inside an occluded area.
4. Aligning two objects or components.
5. Positioning two objects inside an occluded area.

Each task was divided into two subtasks. The first subtask was to locate the object of interest (i.e. focus) and to determine its relationship with the rest of the model (i.e. context). The second subtask was to perform the actual modelling task (e.g. transforming and editing an object or component). In each task, participants were instructed to use a specific modelling technique as stated in the instruction sheet.

5.3. Study participants

Sixteen students (14 male, 2 female) from an undergraduate graphics and multi-media course volunteered to take part in this study. The only requirement was that the participants must have had some prior experience in 3D modelling tasks. Although our study participants were novice modellers, as our previous studies have shown (see Section 3), novice and expert modellers have similar difficulties with respect to focus and context awareness issues. Eight of the participants had some modelling experience with Blender, and the other eight had used other modelling software such Maya. None of the participants had used an MLD previously.

5.4. Data collection

Three types of data were collected in this study: task completion time, quality of the finished model and the participants' opinion regarding the tasks they performed and the environments in which they completed the tasks.

The total time to complete each task (TC) was measured in two parts: the time taken to locate the object of interest (TL) and the time to complete the modifications required to the model (TM). TL was measured because in most modelling tasks, which require object manipulation and transformation, the ability to pick or to select the correct object is therefore critical. TM was also measured to see how much time was spent on doing the actual modelling task.

The quality of the finished models were measured to evaluate the output of each task by each of the participants. The evaluation was done by a single expert, and it involved viewing the finished output produced by the participants against the expected outcome for each task as described on the task sheets. This was felt to be satisfactory because the tasks were precisely defined and the expected outcomes were clearly shown on the task sheets. A score of one to three was given to each finished model (1: incomplete, 2: reasonably finished, 3: perfectly finished). The quality of the models was assessed independently of the task completion time. The reason for this was that the participants were given an unlimited amount of time to complete their tasks.

The participants were also asked to answer a questionnaire upon completion of each task, using a seven-point scale. All the tasks had two questions in common:

- How difficult was it to select a single vertex (or specific object)?
- I was able to effectively complete this task using the system.

Further to these:

- Task 1 asked: How useful was isolating a particular object from the rest of the objects in the model for editing?
- Task 2 asked: How difficult was it to determine the differences between groups of objects or items? andHow important was it to view all other objects while working on a particular component?
- Task 3 asked: How difficult was it to see the relationships between objects in terms of distance and orientation?
- Task 5 asked: How important was it to know the relationship between a particular object and other objects in the rest of the model?

After completing all the 10 tasks, the participants were also asked to answer another set of questions. Questions 1 to 3 aimed to compare the participants' opinions about the two experimental conditions (using a seven-point scale for each condition in each question). Questions 4 to 7, on the other hand, sought the participants' opinions (using a seven-point scale in each question) about the effects of focus and context awareness and depth perception on their work performance in general in MLD experimental condition. The seven questions of this questionnaire were:

1. How easy was it to align objects in SLD and MLD? (a separate scale was given for each).
2. How useful was the depth perception in SLD and MLD? (a separate scale was given for each).
3. How effective was the separation of a particular object from other objects in the model in SLD and MLD? (a separate scale was given for each).
4. Depth perception improved my work performance.
5. The ability to separate a particular object from others improved my work performance.
6. The ability to maintain focus and context awareness is important in order to avoid confusion related to object orientation from occurring during navigation and manipulation.
7. The ability to maintain focus and context awareness improved my work performance.

In addition to these questionnaires a brief interview was conducted at the end of the experiment sessions. The interviews aimed to get the participants' feedback on the strength, weakness and improvements that needed to be made to the five techniques developed for MLD.

5.5. Results

Figure 12 provides a comparison of the mean time taken (in seconds) to locate the objects or components of interest (Figure 12 a) and complete the modifications required (Figure 12 b), as well as the total time to complete (Figure 12 c) each of the five study tasks in SLD and MLD environments.

One-way repeated measures analysis of variance carried out to test for differences between MLD and SLD in terms of the mean time taken to locate the objects or components of interest (TL), complete the modifications (TM) and complete (TC) each of the five tasks showed some significant differences between the two experiment conditions. A summary of the results of these analysis are provided in Table 1. These results show that the component segregation, peeling focus and slicing techniques used in MLD reduced the total time taken to complete tasks 2, 3 and 5, respectively.

We also analysed the recorded time data to see if there was any significant difference between the two experiment conditions in terms of the order of the treatments, or between participants with and without Blender software use experience. No statistically significant differences were found.

In terms of the quality of the finished models, Wilcoxson matched-pairs signed-rank test on the scores showed that for none of the five tasks there was any significant difference between the quality of the models produced in each of the two experiment conditions. Although the number of perfectly finished models was higher for all the tasks in MLD.

Similarly, Wilcoxson matched-pairs signed-rank analysis of the participants' responses to the task questionnaires, completed after each task in SLD and MLD, showed no significant differences between the participants' ratings (on a seven-point scale) for these questions in SLD and MLD. This means that the participants rated MLD same as SLD in terms of the individual tasks they performed, even though they had not used the focus and context awareness techniques of MLD previously. Therefore, it could be argued that perhaps with further exposure to MLD the participants' opinion of the focus and context awareness techniques may improve further.

As mentioned earlier, after all the tasks were completed, the participants were also asked to answer a final set of questions to obtain their overview of the two experimental conditions. Questions 1 to 3 were used to determine the difficulty level of aligning objects, to understand the usefulness of depth perception and to identify the effectiveness of the techniques used for separation of objects in SLD and MLD. Wilcoxson matched-pairs signed-rank analysis of the participants' responses showed significant differences between SLD and MLD for each of these three question, with participants favouring MLD over SLD (see Table 2).

Questions 4 to 7, on the other hand, were used to rate (on a seven-point scale, 1 for strongly disagree and 7 for a strongly agree) the perceived effects of focus and context awareness and depth perception on the participants' work performance while doing their modelling tasks. The results showed that the participants gave an average rating of 4.5 to the effects of depth perception, 6.1 to object isolation, 5.5 to focus and context awareness during navigation and manipulation and 4.5 to focus and context awareness in general in

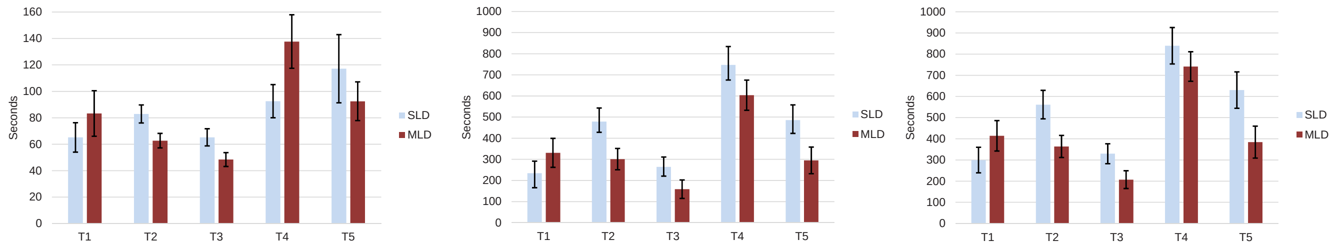


Figure 12: *Graphs of average time taken (and standard error) to locate the objects or components of interest (a), complete the modifications (b) and complete the task (c) in SLD (blue) and MLD (red). Note that the vertical scales are different.*

Table 1: *Summary of the statistical differences ($F_{1,30}$, $p < 0.05$) between SLD and MLD, in terms of the average time taken to locate the objects or components of interest (TL), complete the modifications (TM) and complete the task (TC).*

Task no.	SLD (technique used)	MLD (technique used)	TL	TM	TC
1	Hiding	Object isolation	Not significant	Not significant	Not significant
2	Hidden surface removal	Component segregation	Significant	Significant	Significant
3	Zooming	Peeling focus	Significant	Significant	Significant
4	Wireframe	Peeling focus and context	Not significant	Not significant	Not significant
5	Hiding	Slicing	Not significant	Significant	Significant

terms of improving their work performance. Although the perceived positive effects of depth perception, object isolation and focus and context awareness did not necessarily improve the quality of the models produced in terms of the average scores given to them, as our results show, for 3 of the 5 tasks they reduced the time taken to complete the tasks.

In addition to the post-tasks and final questionnaires, a brief interview was conducted with each of the participants to get their feedback on using the five focus and context awareness techniques developed for MLD. Most of the participants responded that they liked the physical separation between the two layers. They claimed that this feature gave them a better sense of depth when viewing models, compared to viewing them on a conventional 2D display. They mentioned that this feature combined with object isolation and component segregation techniques reduced the problem of selecting the objects or components on the wrong side of the model. They also noted that the ability to view models in both solid and wireframe modes simultaneously in peeling focus, peeling focus and context and slicing eliminated the difficulty of locating hidden objects.

However, the participants also highlighted several issues with the focus and context awareness techniques that need to be addressed. Some of these are:

- In the object isolation technique, having the entire context in wireframe mode caused some difficulties in aligning objects and recognizing distance.
- The disappearance of selected objects from the front layer in the peeling focus, peeling focus and context and slicing techniques caused some difficulties.
- The peeling focus and context technique often removed the context of the model which was relevant to the task being performed.

Table 2: *Summary of the Wilcoxson matched-pairs signed-rank analysis of the participants' opinions about MLD and SLD.*

Question	SLD	MLD	Critical val.	Significant
1	16.0	103.5	25	Yes
2	7.5	70.5	10	Yes
3	13.5	77.5	17	Yes

- The fixed thickness of the slicer in the slicing technique caused some difficulty in seeing objects on the front layer.

5.6. Discussion

In summary, the results of our user study showed that three of the five focus and context awareness techniques reduced the time taken to complete the study tasks, while the other two techniques need to be improved further.

The object isolation technique used in Task 1 did not improve the participants' task performance in MLD significantly. As mentioned earlier, the participants noted that the use of the wireframe mode on both the front and back layers of MLD made it difficult for them to recognize the relative position of objects and components of the model. A solution to this problem would be to show the model on the back layer in solid mode, while the object isolated on the front layer is shown in wireframe mode.

The component segregation technique used in Task 2 improved the participants' task performance in MLD significantly. This technique which separates the components of the selected object onto the front and back layers assisted the participants in recognizing the relative position of the components involved. It can therefore be claimed that the ability to look at the objects or components of interest on the front layer while being aware of its relationship with the context on the back layer reduces the task completion time in MLD.

The peeling focus technique used in Task 3 did also improve the participants' task performance in MLD significantly. This technique enables occluded objects to be seen without visually affecting or distorting the object (e.g. when zooming is used). Thus, the participants could locate the objects or components of interest more easily and realize their relationships with the relevant context more effectively. At the same time, this technique also allowed the participants to work in a less cluttered environment on the front layer.

The peeling focus and context technique used in Task 4 did not however improve the participants' task performance in MLD significantly. The difficulty faced by the participants when using this technique was caused by the fact that the relevant parts of the model (e.g. selected objects) were sometimes removed from both layers due to the clipping process. Consequently, maintaining awareness of the relationship between the objects or components of interest and the context could be difficult. One solution to this problem would be to always keep the selected objects of interest visible on the front layer, even when the rest of the model is peeled away. The basic assumption behind this proposed solution is that the user will always be interested in viewing or manipulating their selected object, and as such it should remain visible even when the other parts of the model are peeled away.

Although the slicing technique used in Task 5 improved the overall participants' task performance in MLD significantly, it did not reduce the time taken to locate the objects or components of interest significantly. As mentioned, the participants noted that the fixed size of the slicer used in this technique caused them some problems because it limited the size of the object displayed on the front layer. An obvious solution to this problem would be to allow the user to dynamically increase or decrease the thickness of the slicer used in this technique.

6. Conclusions

In this paper we presented five techniques developed to improve focus and context awareness in 3D modelling tasks using MLDs. The results of the user study conducted to evaluate these techniques showed that three of them improved the participants' modelling performance by reducing their task completion time in MLD. The study also provided us with a range of user feedback which can be used to improve our five techniques.

We plan to make these improvements, and investigate whether it is possible to use these techniques with other display set-ups that do not rely on the use of MLD. Examples of other display set-ups include the use of large projected displays for context awareness, along with conventional LCDs to provide focus. Other possibilities include the use of augmented reality technology in combination with our techniques.

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