SCALE-BASED EXPLODED VIEWS: EVALUATING OBJECT SELECTION METHODS ON MOBILE DEVICES

by

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DEDICATION PAGE

To my family and friends for their consistent supports during the study.

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ABSTRACT

Many 3D exploded view diagrams are too expensive for use on relatively low powered mobile devices, particularly for large models. In this thesis, we evaluate a low-complexity scale-based 3D exploded view method that is designed to help find and select small and occluded objects from 3D models on mobile devices. The system preprocesses a 3D model by categorizing each object into different layers based on each object's size. The exploded view can then peel the scale-based layers from the object based on user input. In a comparative user study, our method was found to require generally less time than an alternate low cost explosion technique when performing several selection tasks. Moreover, it significantly reduced the number of wrong targets selected. This is important given that our application is targeted for use in mobile-assisted manufacturing and repair environments with a low tolerance for user error.

LIST OF ABBREVIATIONS USED

ANOVA	Analysis of Variance
SBET	Scale-based Explosion Technique
WE	Whole Explosion

ACKNOWLEDGEMENTS

I like to thank Dr. Stephen Brooks and Dr. Kirstie Hawkey for their help in guiding me to do my research at Dal. They not only provided me related resources but also supervised me to design and implement prototype that could increase the efficiency of interacting with 3D model for mechanical engineers in their maintenance operations. Also, I would like to express my gratitude to The Boeing Company for giving me financial support to execute my research in the field.

CHAPTER 1 INTRODUCTION

1.1 BACKGROUND AND MOTIVATION

3D models have been extensively used in manufacturing for several decades. Mechanics and engineers design, examine, repair, and maintain complex machinery with the help of 3D digital models. Digital assistance in large manufacturing assembly becomes more important as the models become ever more complex, far beyond what a human can memorize. Thus, improvements to the process of remembering the inner structure of 3D virtual model is needed, which can increase the efficiency of the work flow of engineers and mechanics. Imagine a mechanic trying to repair or remove a very small broken part of airplane, which is buried deep inside of the engine. The engineer may know what the problem part looks like, but he or she does not know exactly where the part hides inside of the engine or the surrounding environment of that part. Thus understanding context information of the broken part becomes crucial and utilizing a 3D model to help comprehend the context is needed. Using 3D virtual models to mimic the process of finding broken parts and observing the surrounding environment can be helpful and convenient. In addition, digital assistance not only saves the airplane or car manufacturing company significant resources but it can also improve the effectiveness of the repair procedure.

A lot of research has been conducted to allow people to explore 3D models in different ways that help them better understand the overall structure of complex machines. However, many approaches are only applicable to desktop computers and workstations with powerful GPUs and CPUs. Increasingly, mobile devices are being used in industry to improve workflow efficiency on the factory floor. For example, aircraft mechanics deal with complex 3D models during their construction and maintenance tasks. Their time is extremely expensive, because even a small delay on repairing assemblies of a plane has a high cost. The physical distances involved in such an environment are considerable. Our site visits to the Boeing manufacturing plants proved a humbling experience, given that the size of the facilities are on a city block scale and the planes themselves are 250 feet long and 6 stories high. This increases the value of in situ part identification using mobile devices, as the travel time between a location in the plant and a workstation is non-negligible.

Thus mobile devices have been proposed as a means of enabling just-in-time access to 3D virtual models and associated documents. In this thesis, we introduce a scale-based exploded view selection technique which reveals exploded views of 3D virtual models incrementally based on the size of components. We propose this as a feasible method for mobile devices considering their limited CPUs and battery life. The system is evaluated with a comparative user study whose design was informed by ongoing discussions and site visits with engineers at The Boeing Company.

In this research, we are particularly interested in finding and selecting small and occluded components among a complex 3D model. The motivation behind this is the common and frequent scenario of an aircraft mechanic who wishes to repair or replace a broken part. Due to the sheer complexity of the aircraft, mechanics may attempt to look for the same part in 3D virtual model. However, given that a model for a Boeing 747, for example, contains millions of individual parts, it may impossible for the mechanic to recall the names of parts. Although an engineer or mechanic can reference any name of particular a component through an exhaustive name list, it is still inefficient to look for a single name in a list where millions of names are stored.

Text-based data retrieval and analysis have been studied by researchers for some time. The most obvious example today is Google which help users quickly find useful information on the internet, where millions of web pages have been created. Text-based data search applies text pattern matching algorithms where the search or the target expression is compared with every possible match in the webpage or article to locate the exact same expression. Most 3D models are tagged with their related parameters such as name, diameters, volume and so on. Mechanics can retrieve models or parts of models by searching the name of the model or the name of model's properties. However, each small component of the models that mechanics use at Boeing Company has extremely long names, consisting of several parameters, so they are difficult to remember. Therefore, simple text searching would not be possible in most cases. Also, the same part may be used in multiple location on the plane. Thus they require alternative ways to search for those parts. One of the key pieces of information they have is the spatial location of each component within the 3D virtual model. This knowledge, combined with exploded view selection on mobile devices may help facilitate the selection of occluded parts in this kind of environment.

1.2 RESEARCH QUESTIONS

With our implementation of scaled-based exploded view techniques on mobile devices, we test two hypothesizes:

(1) The scale-based exploded view technique performs better than a whole-model exploded views technique for finding small and occluded parts within 3D models, in terms of time required and accuracy.

(2) The complexity of 3D models and the size of the searched for target affects the performance of a scale-based exploded view technique.

1.3 OBJECTIVES

This research is part of the Boeing mobile graphic project in which we create novel methods to help mechanics effectively conduct their work. Our main goal is to design and evaluate a method targeted for use on mobile devices which applies scale-based exploded views to help mechanics search occluded objects within virtual 3D model. We evaluate the performance of our scale-based exploded view technique by comparing its results with another approach called whole model exploded views. This is an alternative method capable of running on mobile devices that explodes every component in the 3D model at once. Our primary purpose is to help mechanics search for small and occluded targets among complex 3D virtual models with the help of mobile devices. We therefore render 3D models with different levels of complexity and size so that we can evaluate how these parameters affect the speed and accuracy of finding targets with the two exploded view approaches.

1.4 CHALLENGES

Simply rendering complex 3D models with a large amount of detail on mobile devices is difficult. If in addition, the system is simultaneously required to perform expensive real-time calculations, then it can quickly become intractable. It was stated by Li et al. [1] that their system designed for interactive exploded view explorations could only generate effective visualizations of models with up to approximately 50 parts on a desktop computer. Beyond that size it required too much computation time to determine blocking and contained parts. In order to go beyond this limit, we need to simplify two things: the models and the calculations on those models. As long as we can still recognize each individual part, removing small details of vertices and triangles to simplify the model is one necessary step. And in order to simplify the calculations of relationship between different components, we must allow parts to pass through each other during the exploded view process. Although this violates the blocking constrains rules which are commonly adopted by exploded view techniques, it may not affect the result of finding small and occluded parts of a complex 3D model since relationships between parts are not as significant a concern during the selection process, as the relationship is in a process of assembly or disassembly.

Another issue that needs to be addressed is the relationship between the mode of input on mobile devices and object selection. We use the mouse to interact with 3D models on a desktop computer, which allow us to select any object as small as a pixel. But it is hard to be precise on mobile devices which are usually controlled with a touch screen and fingers are the mode of interaction. Using a touch pen or another more accurate tool instead of a finger to select small parts of virtual model can be considered as one of alternatives; however, in the target environment, it is easy to lose or confuse these small tools because of the presence of large number of small assemblies while repairing. Also, in some cases small foreign objects are not permitted. Therefore, we still need to choose fingers as our main interaction tool to communicate with 3D models on a mobile display and hence the system should enable functions to select small objects. To overcome this problem, we can first make the selection area of small objects bigger, so that objects falling into this area can be selected when the tip of finger makes contact with it, even though the finger doesn't touch the exact objects.

Visual clutter is another problem that needs to be solved relating to exploded view techniques. Exploded view techniques change the spatial arrangement of each component so that it can reveal internal parts which are not visible in the first place. However, when the model is complex, separating every part in 3D space could result in visual clutter which makes it difficult for people to search for a certain object. Two different methods for conquering this issue have already been proposed: compact [23] and local [26] explosion techniques. Because there are many similar objects in typical 3D mechanic models such as turbo or engine, Kalkofen et al. proposed compact explosion method so that only one representative part is exploded among many similar objects. Sonnet et al. proposed local explosion approach so that only small portion of 3D model will be exploded and therefore it reduces visual clutter. Kalkofen's approach brought in heavy calculation which is not suitable on mobile devices. In our research, we take sonnet's method one step further and allow user to remove less important parts. Additionally, the small screens of mobile devices make it harder still to display all parts. As we will show, by screening the selection process layer by layer, the user can remove sets of parts that are not target objects. In this way, at every stage, only limited parts are displayed on mobile devices mitigating the effects of visual clutter and making it easier to find target objects.

1.5 CONTRIBUTIONS

Our scale-based exploded view method is the first 3D exploded view technique designed specifically for mobile devices that improves the speed of finding and selecting target components in 3D models. With the help of our application which enables just-in-time access, mechanical engineers can quickly locate broken parts and perform repair or replacement to targets. This is could be very crucial because it can save mechanics precious time and therefore save huge amount of money.

Although our application can't be directly applied to 3D models with thought or millions of parts, we can segment large 3D model into several small parts and perform explosion on each small model. In this way, our application can be assisted as a bridge between extremely complex models and it's usage on the filed operation. Below is a diagram shows how our application can be used in an actual work flow. As we can see from Figure 1 that a mechanical engineer starts SBET application when he or she is in position of place where it has components needs to be repaired. Then it will send GPS request from SBET to the Indoor GPS system, the system will analyze the data and return results to backend server. The backend server then return related 3D model in that repaired area to the SBET interface. Now the mechanic can perform explosion techniques using SBET on the 3D model and repair or remove broken components.

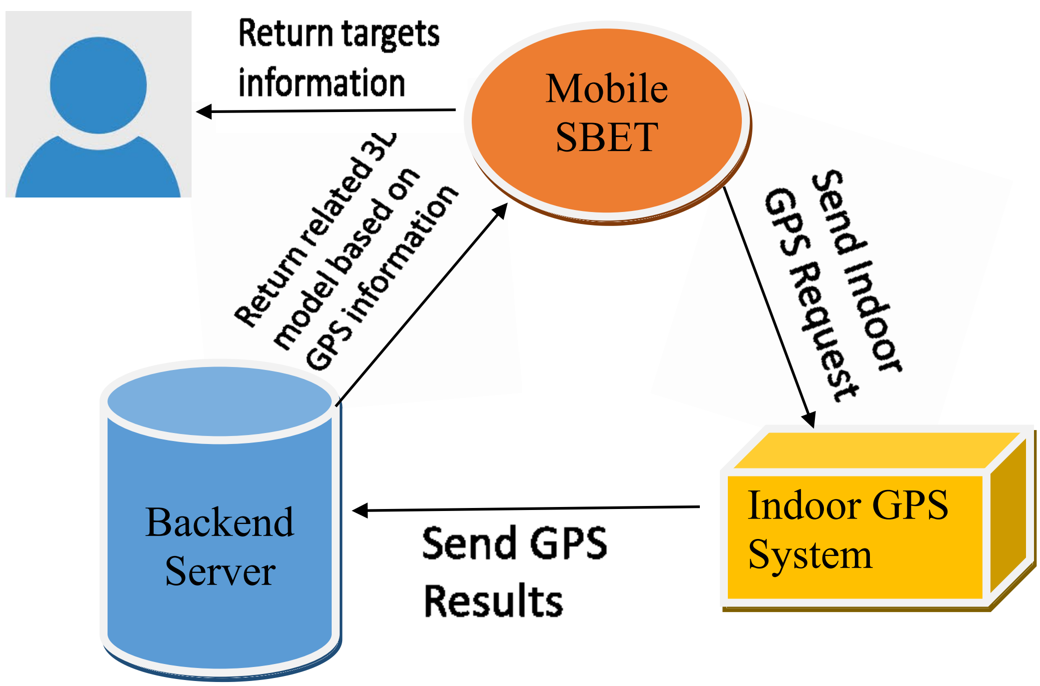


Figure 1: Overview of SBET usage on the work flow of mechanical engineers.

To confirm this, we conducted a user study to evaluate its performance by comparing it with the whole model exploded view approach. We analyzed study data and presented results which concluded that SBET performed generally better on the task finishing time than WE. Also SEBT significantly eliminated the wrong targets comparing with WE. Moreover, we analyzed limitations of SBET on mobile devices, which can be very helpful for further researchers to conduct experiments considering those feedbacks.

1.6 OUTLINE OF THE THESIS

This thesis consists of five chapters. Chapter 1 is a simple introduction which discusses the background, motivations and contributions of our research work. Chapter 2 on prior work presents the state of the art related to this thesis. Chapter 3, states the methods and background theory that we used to solve the research problem. A controlled user study which compares two methods and result of the analysis are described in Chapter 4. Chapter 5 covers conclusions, future work and a summary of the thesis.

CHAPTER 2 PRIOR WORK

A virtual 3D model is a combination of several objects physically predefined and spatially prearranged in a three dimensional space. The biggest challenge of depicting a solid 3D model is occlusion among structures, which poses problems for understanding relationships between each component and for selection of sub-objects. Different methods have been proposed to tackle the problem of understanding and interacting with internal components of 3D models. There are three main techniques that are used to interpret the inner structure of a technical model: ghosted views, cut-away views and exploded views.

2.1 GHOSTED VIEWS

Ghosting or x-ray visualizations render a transparent view from outside a surface to reveal internal structures. Commonly, people use ghosting view techniques extensively in the area of mechanical engineering and medical illustration since they regularly deal with 3D model of assemblies and human anatomy. One examples of this is shown in Figure 2 which shows 3D car and plane models rendered with partial ghosted views [2] [3]. Researchers in the field of computer-aid design and computer graphics have been studying different approaches for generating transparency levels of 3D models. There exist several books and manuals that discuss standard approaches for the generation of transparency. For example, Hodges and Thomas outlined rules and principals for processing transparency to convey important information of location of occluded parts within models [4] [5]. Hamel et al. presented an approach of rendering line drawings containing transparency on computer using OpenGL-based renderer, which is guided by analysis and rules given by Hodges. [6]. However, this rendering system can't visualize different levels of transparency.

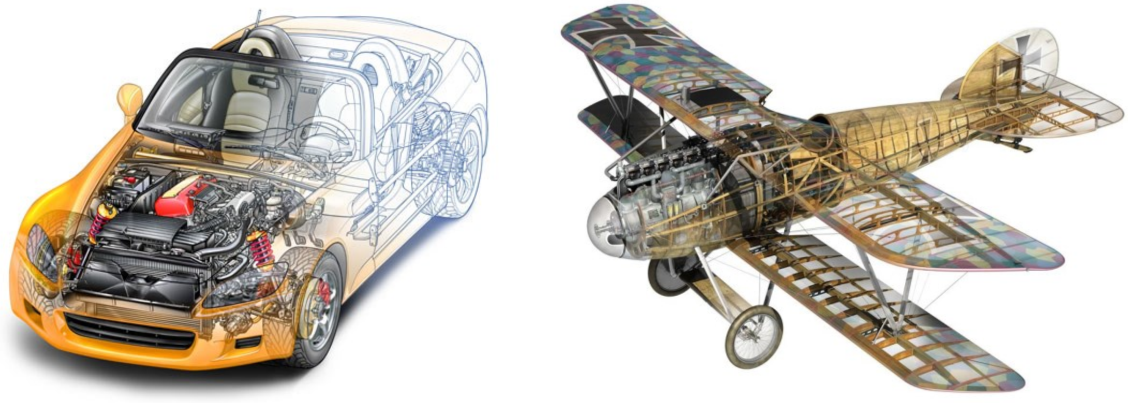


Figure 2: Ghosted views of a car [2] and a plane model [3].

However, visualizing different levels of transparency automatically within 3D models is not yet a solved problem and many prototype systems have been presented to address specific problems. In early work, Kay et al. used a non-liner transparency algorithm to improve the realism of computer synthesized images by making assumptions about the geometry of each object and their conditions under which they are viewed to achieving the refractive effect [7]. In addition, inspired by artist's use of line, Interrante et al. proposed a method for texturing transparent surfaces with uniformly spread opaque stroke to help visualize layered surfaces in radiation therapy treatment [8]. Rheingans and Ebert [9] introduced a physics-based rendering process that utilizes non-photorealistic rendering (NPR) techniques. This is a volume illustration approach designed to improve the structural perception, shape, orientation, and depth relationships in a volume model by the addition of illumination effects. One example of this approach is presented in Figure 3. We can see from the comparison that their method enhances the internal structure and illustrated as a more realistic image.

The systems described above are based on the concept of a static or semi-interactive design, wherein the system determines the density and direction of transparency. But these approaches are not suitable for real-time systems, especially for finding small and occluded objects within 3D models. This is because the target objects can change constantly which requires real-time transparency assignment. In addition, ghost views can only help view occluded parts and rather than select those objects inside of 3D model.

An interactive real-time view-dependent transparency method was presented by Diepstraten et al [10], which includes a hardware-accelerated depth sorting algorithm to dynamically change the transparency. Figure 4 shows an example of their test images created by the system. This method may solve the assignment of real-time transparency for searching occluded parts but it does not support multi-transparency where the target objects are blocked by more than one object. For example, finding the deepest objects in the center of a complex 3D model could be difficult for this method.

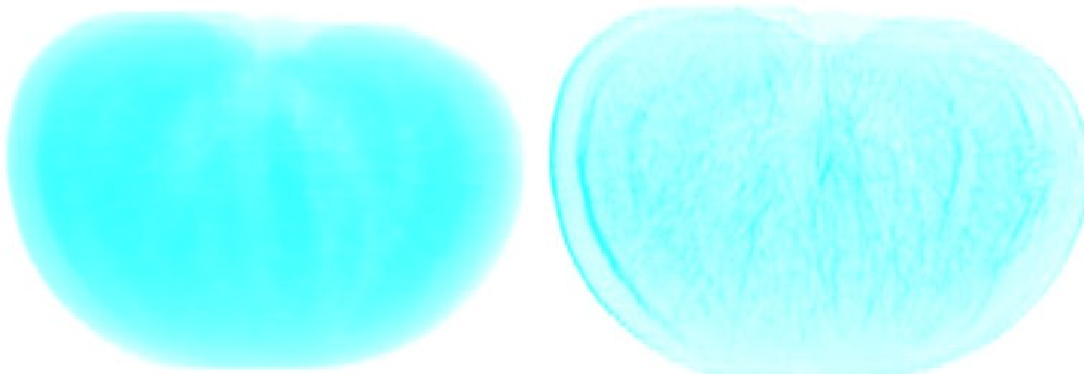


Figure 3: Standard atmospheric volume rendering of tomato (left image) versus a boundary and silhouette enhanced tomato (right image) [9].

Figure 4: Difference between standard transparency blending in (left image) and view-dependent transparency blending in (right image) [10].

2.2 CUT-AWAY VIEWS

Cut-away views are another method used extensively to handle occlusion within 3D models. In order to have visual access to the internal parts of 3D models, we can remove occluding parts to communicate to internal structures. Hodges [11] and Netter [12] introduced the prescription that designing cuts on volumetric data should follow cognitive rules for reconstructing the missing geometry mentally. However, static cutaways can often only reveal little information and require a lot of manual operations. A low level automated cutaway technique was described by Konard-Verse et al. [13]. They used a deformable clipping plane for selective virtual resection. It fulfilled two functions required which are: intuitively and precisely specifying a virtual resection and producing visualizations of effective resections immediately. Weiskopf et al. [14] proposed a more advanced clipping method that uses complex geometries for volume clipping instead of common plane clipping, which enable users to interactively select and explore different regions. By combining clipping and shading, they were able to generate depth-based clipping which gave in-detail perception of model structure. Figure 5 shows an image of CT data made by the system.

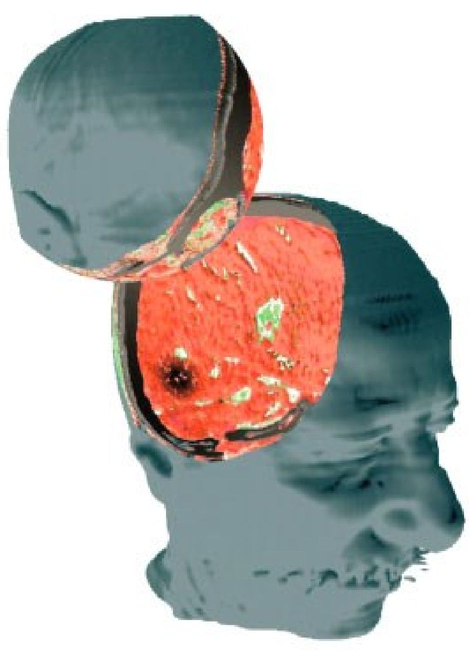


Figure 5: Depth-based clipping in an illuminated CT data set [14].

Viola et al. introduced an importance-driven method to make parts with the highest priority clearly visible first [15]. They rendered occluding objects between features and the viewpoint sparsely so that the features with highest importance were visually emphasized. An example of using their method is shown in Figure 6. The system cuts away parts between the viewpoint and features since the internal organs were classified with higher priority.

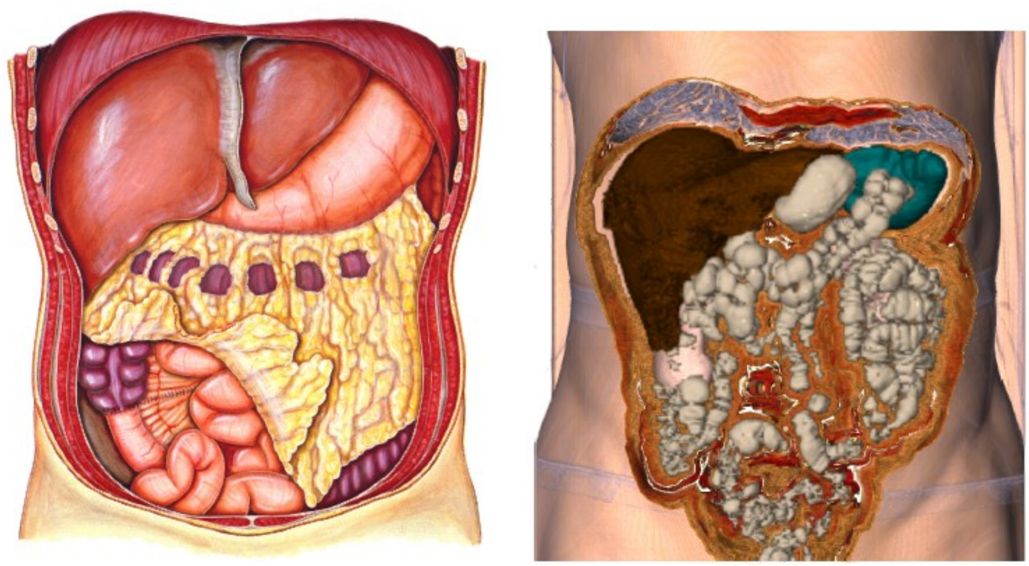


Figure 6: Comparison between an artistic medical illustration of the abdomen (left) and the importance driven cut-away method (right) [15].

In later work, some tools have been developed to create editable cutting regions so that users can define their own cut [16]. A more subtle interactive cutaway technique was proposed by Li et al. [17] to support authored generation of cuts with editable auxiliary parameters.

Although cut-away techniques are an effective way to remove occluding parts to unveil internal structures, it still does not resolve problems of selecting small or occluded objects within 3D models. This is a cut-away method only shows part of the target object by removing occluding components and this makes the target components hard to select if the target components are located deep inside of 3D model. This is even harder for users to select on touch screen devices since one's finger needs a bigger selection area as compared to mouse selection on a desktop computer. In addition, users may lose the related context around the target parts and select the wrong parts.

2.3 EXPLODED VIEWS

As we mentioned in the previous section, the main limiting factor of the above methods is the loss of surrounding contextual information, and context is one of essential aspects required for comprehending the overall structure of 3D virtual models. To overcome this, exploded view techniques were proposed as an alternative to browse volume models by McGuffin et al. [18]. In their work, the system let users cut into, open up, spread apart and peel away parts in real time, making the interior visible while still retaining context. However, the explosion is controlled manually. There are other systems that produce exploded views such as Driskill et al. [19] and Rist et al. [20], but the views are static. Exploded view techniques are a kind of deformation method that modifies the spatial arrangement of features to reveal hidden content.

Bruckner et al. proposed a semi-automatic explosion technique to interactively inspect the interior of a volumetric dataset in a feature-driven way which retains context information [21]. But a limitation this type of system is that users have to decide the explosion directions and blocking relationships for all parts in the model, which is a tedious task when dealing with even moderately complex models. Agrawala et al. suggested an algorithm that can compute the order and direction in which parts can explode without breaking blocking constraints [1]. They also proposed design rules and principals for creating effective assembly instructions with the help of exploded view diagram underlying lines and arrows. Based on cognitive psychology research, their system can help users quickly build a complete assembly. Later Li et al. went one step further and implemented an interactive exploded view diagram automatically generated by the system. They used explosion graphs to encode how parts explode with respect to each other within part hierarchies [22]. Figure 7 shows a turbine model automatically computed to expose the user-selected target part labeled in read. Another feature of this system was that user can predefine a list of targets and the system would generate exploded views only contains those targets and the users could then continue to expand exposed parts. However, the pre-computation process of constructing contact, blocking, and containment relationship is extremely costly. Also, there are several limitations to their system which are: an inability to separate atomic parts with certain complex interlocking relationships, sensitivity to noisy or irregular surface geometry and the potential possibility of creating visual clutter when there is a need to explode internal parts with many blocking parts surrounding.

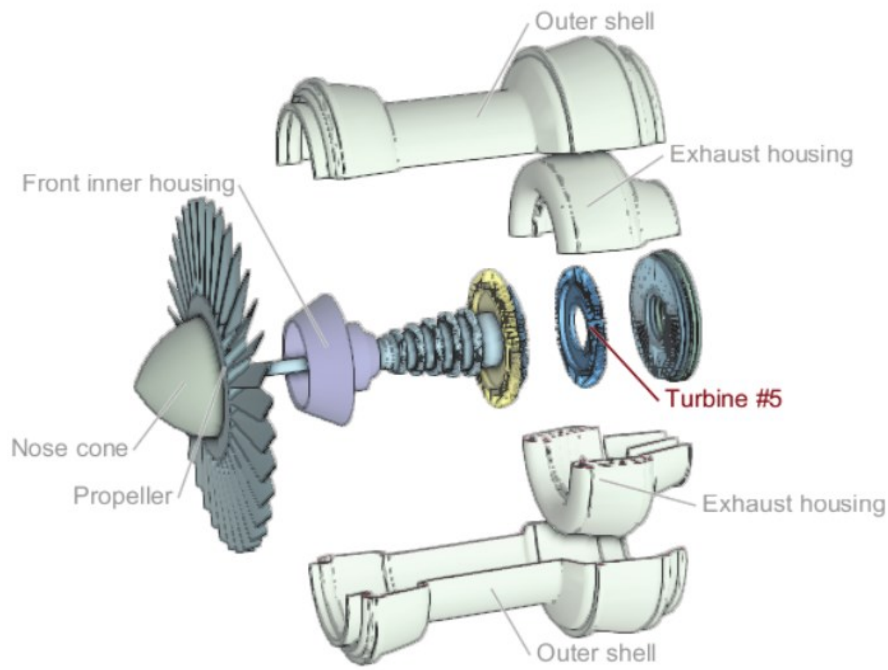


Figure 7: An exploded view diagram generated by Li et al.'s system [22].

A lot of research has followed Li et al.'s work, one of which offers a solution to the visual clutter problem which happens when many small pieces explode together. Kalkofen et al. proposed compact explosion diagrams taking into account the similarity between objects [23]. The system recognizes a representative among several identical group objects by evaluating the quality of their potential exploded view and only these representatives are exploded. In Figure 8, as we can see, only one branch of assemblies is exploded and other branches stayed still. This method could be very efficient when there are a lot of similar objects within 3D models and if we only try to understand the structure of models. However, it could fail in the circumstances where we want look for target objects inside the model which might not be exposed if it is not selected as a representative. Also, it presupposes a significant amount of duplication within the model.

Figure 8: Compact Explosion Diagrams [23].

Later, Ruiz et al. presented similarity-based exploded views which the system used information-theoretic technique to generate exploded views by partitioning the high volumetric data into different number of slabs [24]. Usually, exploded parts are independent from each other and each object can be considered as a separate part. However, their method created exploded parts by segmenting the complete model into different sizes of small parts and exploded these layers. Figure 9 shows an example of using this method. As we can see from Figure 9 that this approach applied a set of cross sectional plane to segment model into different parts in order to reveal internal structures. The problem of this approach is that it may destroy the potential target objects if user wants to look for certain parts. And also, some target objects can't be completely separate from others, which make the selection of individual parts difficult. Moreover, since this method explodes 3D model based on the size of partitioning plane, it would be very hard to select small and occluded targets which partitioned into other parts into the same plane.

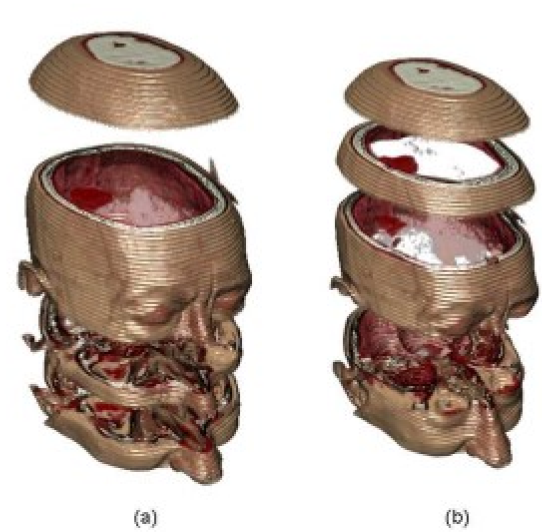


Figure 9: (a) The volume partitioning and (b) the slice grouping approaches applied to a brain model.

A force-based approach was proposed by Bruck and Groller to interact with objects of interest. Based on the given constraints, “focus objects” apply an explosion force emanating from itself to cause surrounding parts to arrange, so that the targets can be exposed to the users [25]. This method was also compatible with view-dependent explosions which were described earlier. Another force-based explosion technique presented by Sonnet et al. [26] uses a small red cube called probe to interactively control the local explosion in order to reduce the visual complexity of explosion diagrams. Figure 10 illustrates the exploration of a human heart using this method. Sonnet et al.’s work was one the of extensions of the visual access distortion technique by Carpendale et al. [27], which opens the line of sight by pushing away surrounding parts. An example of view-dependent distortion technique is shown in Figure 11. It is shown on the graph that an invisible path between focus object and sight was generated reveal sections previously obscured.

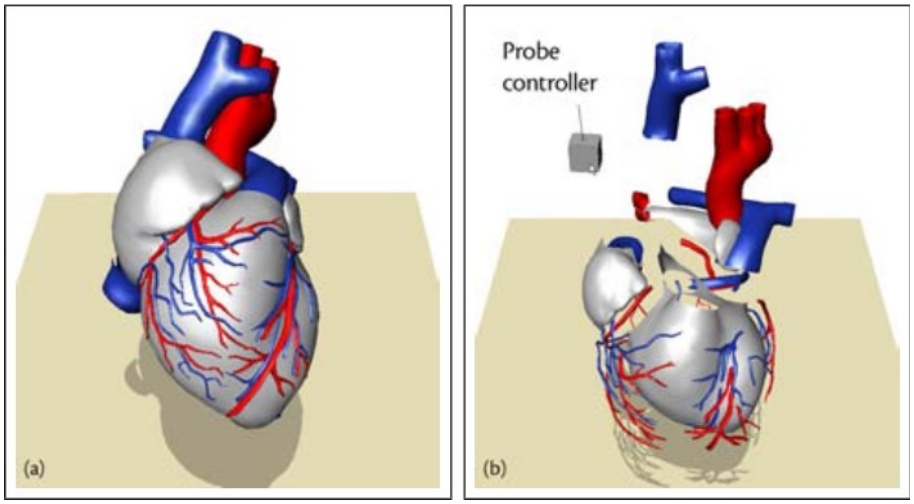


Figure 10: Effect of a 3D probe. Objects are displaced when they are covered by the probe's scope [26].

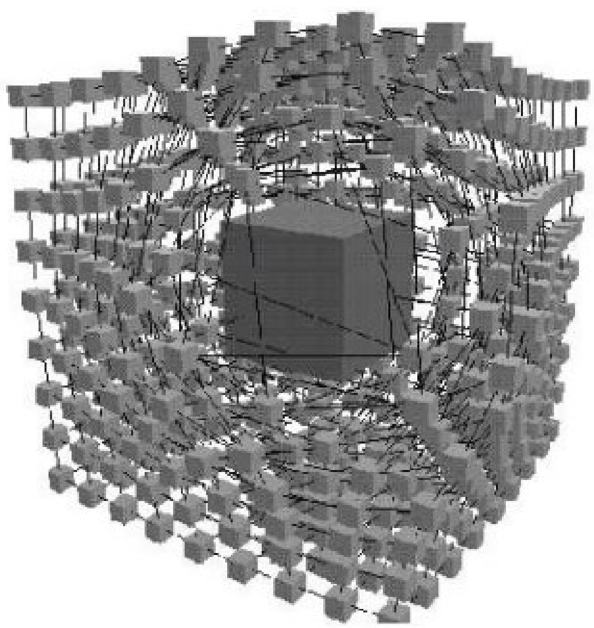


Figure 11: Viewpoint-dependent distortions of three-dimensional graphs [27].

2.4 MOBILE GRAPHICS

Since our research topic concerns finding small and occluding targets within complex 3D models on mobile devices, it is critical that we discuss related work about mobile graphics in general. Also most of exploded views method are performed on the desktop machine, which has powerful GPU and CPU to do heavy calculations and complex rendering. Thus it is essential to compare performance between desktop and mobile devices to see how method difference can fill the hardware gaps between two platform machines. The popularity and capabilities of mobile computing devices such as tablets and cellphones have been greatly increased the last several years and 3D games and maps have been developed for those devices, enabled by hardware acceleration. However, performance still does not approach that of desktop machines or dedicated game consoles. For example, one of the best mobile graphic processing units today is Adreno 330 manufactured by Qualcomm Company. The core speed of it is approximately 400 MHZ comparing to 800 MHZ core speed of GeForce GTX Titan Black on a desktop by NVIDIA. Desktop graphic cards are two times faster than mobile GPU just in frame speed. In addition, processors of mobile device such as Nvidia's Tegra 3 or Apple's A6X pale in comparison to the PC chips from Intel or AMD. Desktop still shows better performance in other aspects such as memory size and hard drive compared to mobile devices.

A quantitative study was also conducted by Mochocki et al. about the power usage of mobile 3D graphics [28]. They evaluated different factors impacting energy consumption of handheld devices while running a 3D graphics applications and concluded that dynamic voltage and frequency scaling (DVFS) in mobile 3D graphics processing had great potentials to improve. Figure 12 [28] demonstrates a graph showing relationship between energy required and battery capacity from 2002 to 2009. It is clear that the capacity of the battery has not significantly improved while the needed energy for mobile devices has increased dramatically. Therefore, battery life and related performance should be taken into account when designing scale-based explosion technique on mobile device. Our method applies simplified algorithm to minimize the computation of CPU, so that the application won't consume all the battery and still it can perform well.

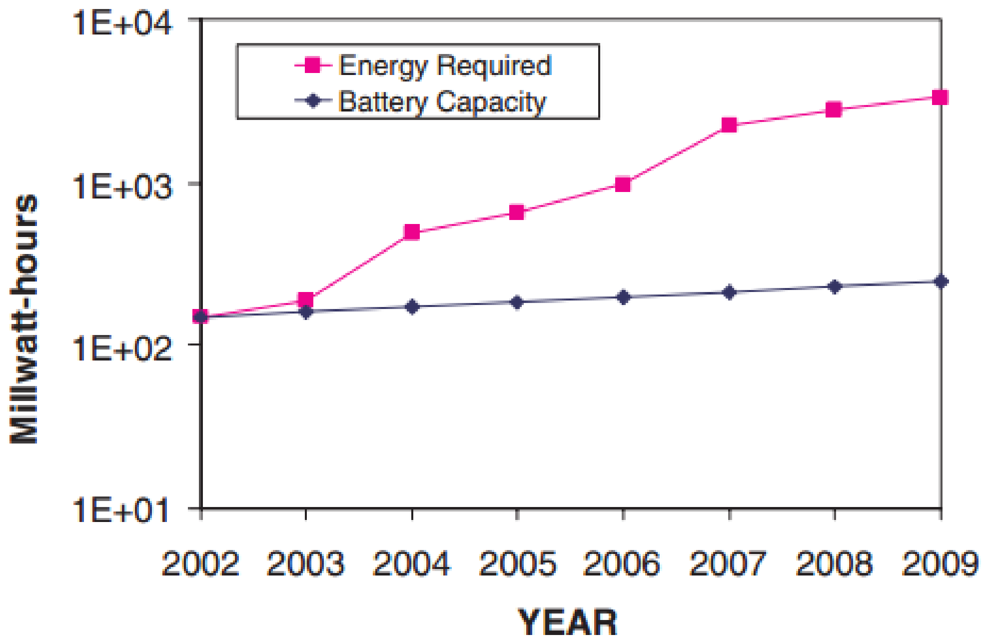


Figure 12: Disparity between mobile 3D graphic energy usage and batter capacity [28].

There are some approaches proposed to achieve a better rendering experience on mobile devices that is comparable to desktop computers, one of which is remote rendering. Using a workstation with enough computing and networking resources as a rendering server, the system deliver rendered images to mobile devices. An improved method of remote rendering was introduced by Shi et al. [29] in which the system uses multi-depth remote rendering methods to reduce interaction latency when transferring data from the client side. However, the system still can be overwhelmed when too much motion is produced by the client application.

2.5 THE "FAT FINGER" PROBLEM

The "fat finger" problem, as it is termed, is another issue that happens in many mobile applications. When the user uses fingers to interact with the device, a relatively large portion of screen area is covered. Most existing mobile platforms use only a single point within the contact area to do 3D object "hit testing", and this creates a problem in that users believe they are selecting the target while the system thinks they are not. And also the users cannot see the selected target when it is smaller than tip of finger and most devices cannot sense the finger until it's touching. So, how to a select target that is smaller than the size of user's finger remains an open problem.

One obvious solution to this problem is make user interface large enough so that people can select it with confidence. Another method, called the iceberg target technique [30], makes the selection target larger than the target object itself that is being selected. As we can see from Figure 13 that as long as our finger falls into the larger surrounding area, the target object within that area will be selected.

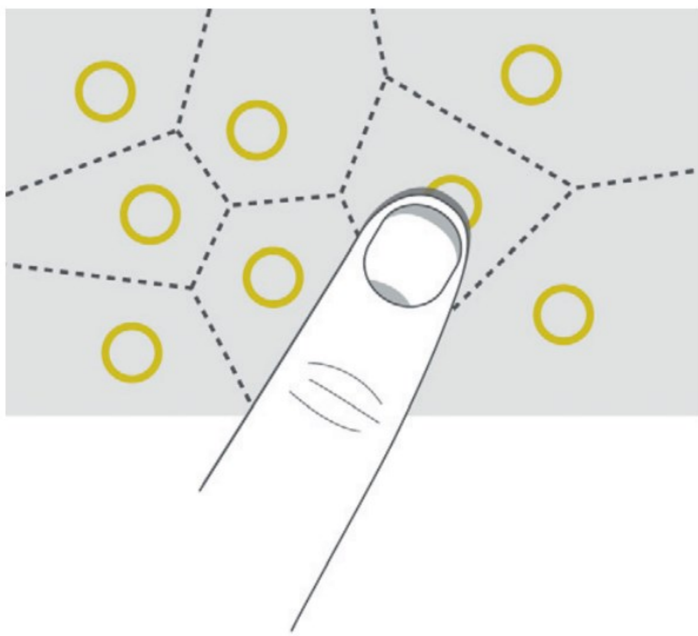


Figure 13: Iceberg targets technique example [30].

However, when the target is in very dense environment, we could still miss selecting our target using the two methods described above. An alternative "Escape" method was proposed by Yatani et al. [31] performing accurate object selection by examining the direction of users' finger when its slides off an object. Figure 14 shows us an example of this approach. Users can select the yellow target by sliding their finger in an indicated direction (shown right in the figure). However, a disadvantage of this method is that the system needs to label the user interface with a direction for sliding selection and multiple similar directions for objects may overlap at the same position.

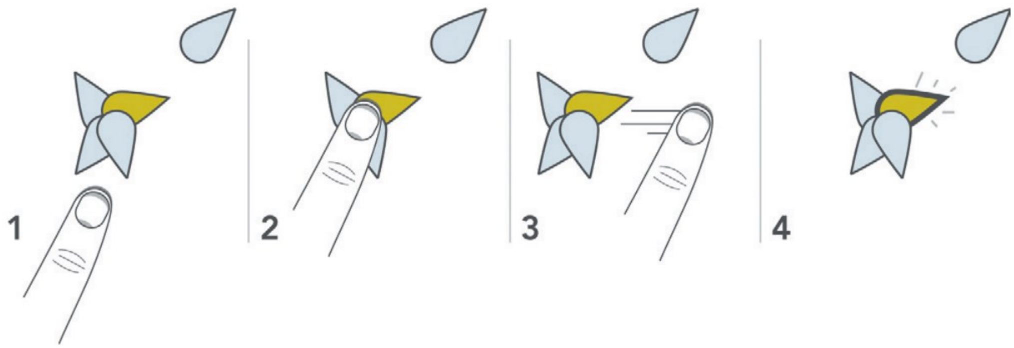


Figure 14: The "Escape" technique selection process [31].

CHAPTER 3 SCALE-BASED EXPLOSION TECHNIQUE

So far, we have reviewed related research about technical model illustrative methods, mobile graphics and the “fat finger” problem. In this thesis, we will compare exploded view techniques designed for mobile devices to enable the selection of small and occluding objects. To this end, we simplify the process of computing relationships between parts by allowing parts pass through each other and group sets of objects based on bounding box size. Even though allowing objects to pass through others violates blocking constraints, mobile devices have very limited CPU and GPU power, and with this approach we are able to present exploded views of up to 450 parts in real time. But given the necessity of simplifying the exploded view approach, it becomes critical to study how best to maintain usability and accuracy under such constraints.

The benefits of using SBET over complex algorithms described in the research of Li at al. [24] are listed as below:

- Battery Life

  As SBET is a simplified exploded technique performed on mobile devices, therefore it requires less power on CPU calculation and rendering pipeline. So the system won’t consume too battery life. However, if the complex method performed on the same mobile device, it would need much more power.

- No need for calculations of blocking and containing relationship between parts

  Our SBET performs interactive exploded view diagram without considering blocking or containing information, and this is useful because the cost of calculating relationship between components are expensive. For example, if a large components contains 10 parts and each part is also contained within other parts, the process of analyzing relationship is time consuming even on desktop machines. Since our purpose is to find occluded targets within models, so we don’t need to be concerned about how each part is related to another.

- Handle more geometry than a complex method in the same devices.

  As discussed in the paper of Li at al. [24], their interactive exploded view technique can only perform explode models up to 50 parts. However, using SBET method, we are able to explode models up to 450 parts and still present good results as it is a huge improvement comparing to existing complex approaches.

Our method for exploring 3D models on mobile devices and assist in locating small and occluded target components is related to the approach described by Sonnet et al [26]. The author used a 3D cube as an interaction tool to locally explore parts of a model by pushing each nearby component away. The 3D cube has a limited area of detection used to explore parts. We refined several aspects of this technique to make it appropriate and feasible for finding and selecting small and occluded targets on mobile devices. First, we expand the scope of interaction area to encompass the whole model and, secondly, we permit exploration on a layer by layer basis. Each component of a model can be categorized into one layer based on the bounding size of this object and only the objects in the current layer can be exploded and explored.

3.1 3D INTERACTIVE PROBE

The 3D probe is our main interactive tool for exploring the model and finding occluded targets. As we can see from Figure 15, the whole structure contains three components: the visible 3D probe, the transparent cap and the sphere collider.

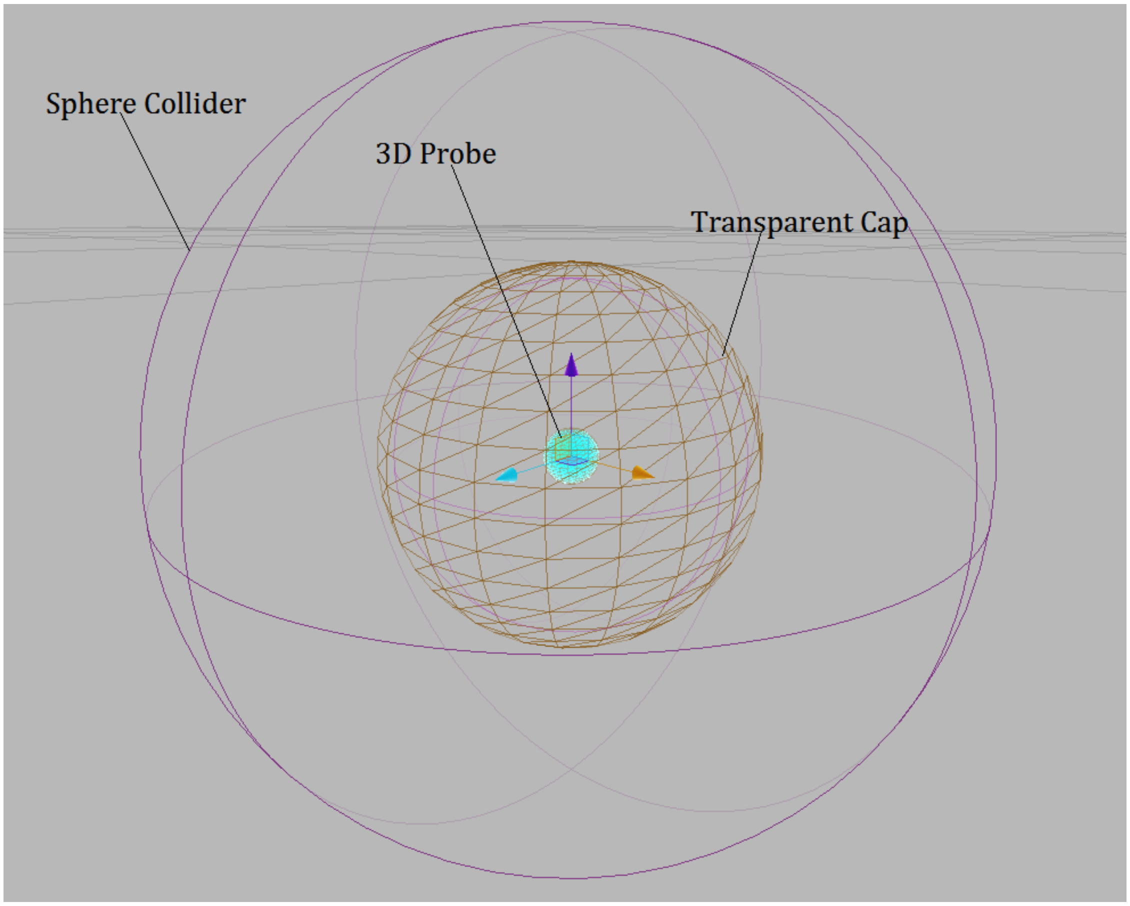


Figure 15: Structure of 3D Interactive Probe.

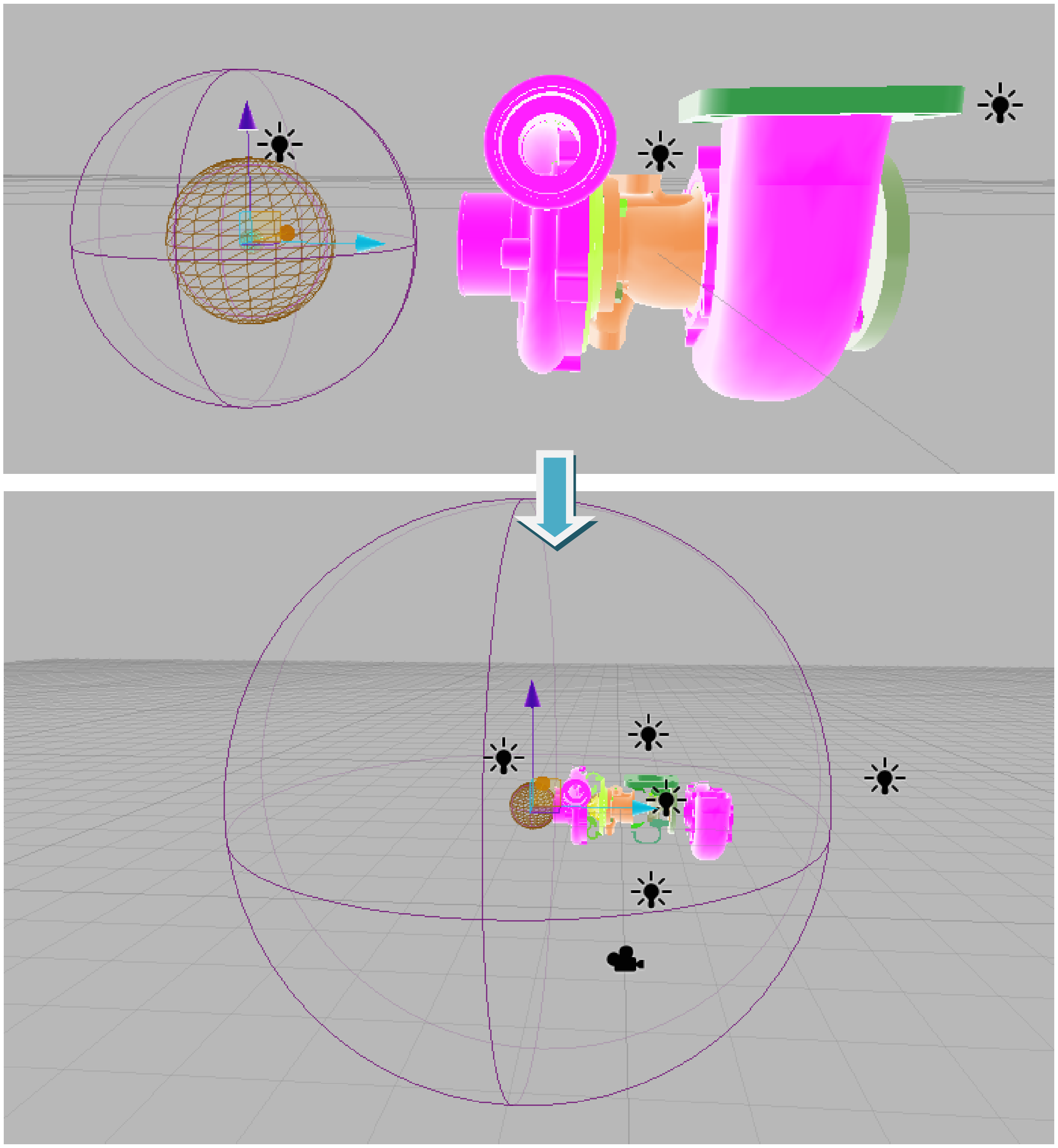


Figure 16: Before (top) and after (bottom) probe detection of collided objects.

Transparent cap (shown blue) is a child component which is slightly larger than the 3D probe and covered by transparent material so that users always have visual access on 3D probe. The purpose of the transparent cap is to mitigate the fat finger problem that users may encounter when they try to move the 3D probe with their fingers. The principal behind this is simply the expansion of the contacting area during the selection process. As long as the users' fingers make contact with the transparent cap, the 3D probe will follow the path of the finger sliding on the screen.

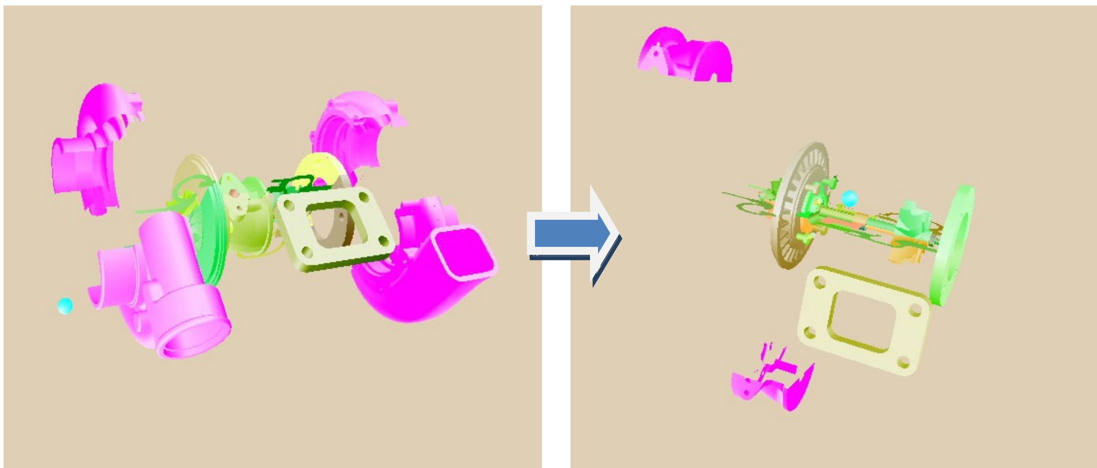
The sphere collider (shown green) is a 3D circle whose function is to detect if there is any 3D objects that are sufficiently close to the probe. When we move the probe close to any part of 3D model and the sphere collider makes contact with colliders of mechanical components, the sphere collider can detect that there are objects within range and will subsequently expand its scope to cover the entire 3D object and perform related the necessary explosion. This process is shown in Figure 16.

3.2 THE EXPLOSION PROCESS

In our method, we employ a 3D interactive probe whose effects can manipulate an entire layer of objects. Specifically, the probe is covered by a small invisible triggering area which is our sphere collider as described previously.

The entire process is briefly shown in Figure 17. When the probe is moved close to the 3D model, the sphere collider of the probe collides with the box boundary of any component within range. At this stage, we say that the probe is activated and the model will start layering its objects by the size of each object's bounding box. Each bounding box is a cube covering the entire object. Usually, the largest components will be categorized into the first layer and the number of components in this layer entirely depends on the comparison between the volume of components and value of that layer's threshold.

The system automatically encodes the first layer's components with the same color (bright green) so users obtain a better sense of which objects are exploding. All objects in the first layer are then exploded away from the probe as shown Figure 17(a). At any time from this point, the user can progress to the next layer, having determined that the target object is not within the current layer. In the subsequent layer, as shown in Figure 17(b), the largest parts which belonged to the first layer disappear. The threshold then decreases by half so that the system can further segment the set of second largest parts from the model. These are now classified into the second layer and these components are color coded in with the same distinctive color of the active layer (bright green) and will be exploded at the users' direction. We can continue this process until no further layers remain in the model and the system reaches the final layer that contains the smallest components, as shown in Figure 17(c). At any stage the user can select the target object of interest whether they are being exploded or not.



(a) The first layer explosion (b) The second layer explosion

(c) The last layer explosion

Figure 17: Work flow of scale-based exploded view.

The set of thresholds T_i, are used to divide the model into different layers, and are set relative to the volume of the model. The initial value of the largest threshold T_0, is determined by the size of the largest objects of the 3D model. For each model, we calculate the size of largest components R and divide R by two and make it equal to T_0. Each sub-object's volume is calculated based on the bounding box of the sub-object. Each sub-object has a bounding box property which contains the length, height and width values of the bounding box *B*. V_j represents the volume ($B_x \times B_y \times B_z$) of sub-object *j*. When V_j is larger than the current threshold, sub-object *j* will be classified into the current layer, will be rendered in the same color (green color) and also will be exploded concurrently as we can see in the Figure 17(a). The four green components belong to the one layer and explode accordingly. The series of thresholds T_i, decrease by half in each subsequent layer, and the current effective threshold is incremented when the "+" and "-" buttons are pressed.

The number of sub-objects in each layer is determined by the comparison between threshold and each object's volume, meaning that the number of components in one layer is not fixed. For all objects with the 3D model, if any sub-object's volume value is larger than the current threshold, it will be categorized into one layer and added to the ArrayList data structure for that layer.

However, in order to reduce visual clutter, we make sure objects in every layer cannot exceed an explosion number which can be adjusted automatically by the system. We set the initial explosion number to 10 and this value is tested manually to all three models so that all explosion objects can fit into the touch screen. As the threshold and explosion components get smaller, the system can explode more objects by adding 5 to each layer to set its maximum explosion number without having visual clutter since they can all fit into the screen as we can see their comparison between Figure 17(a) and Figure 17(c). In the Figure 17(a), there are only 4 objects exploded, but there are more than 20 objects exploded in Figure 17(c) and we are still able to clearly distinguish between different components. However, if the potential explosion number exceed the maximum explosion number, then we add those extra components into next layer.

3.3 APPLICATION INTERFACE

Figure 18 shows our prototype implemented for the Acer android tablet using the Unity 3D Game Engine as a development platform. There are three main sections in our system: the left side control section, the middle interaction view section and right side overview map section.

In the left side control section, there are several functional buttons which control basic interactions with the model. Every 3D object has three directions of motion: x axis, y axis and z axis. The z axis movement of the 3D probe (which is a small red ball and represents the main interaction tool) is controlled by the embedded accelerometers of the mobile device and it can be turned off or on by the buttons: “Start Tilt” and “Stop Tilt”. As part of our research, we are interested in leveraging the tablet’s capabilities to reduce the visual complexity of the interface. The x and y axis of 3D probe are controlled by the movement of the finger touch. Once selected, the probe follows the path of a sliding finger on the screen.

There is an additional control panel for very fine movements. The directional panel near the top left corner of the screen is used for adjusting the movement of the probe by a very small degree. This enables slight adjustments of the probe’s x and y coordinates. Also, finger movement enables rotation of camera at four directions which are x, -x, y and –y. The directional panel near the bottom left corner of the screen is used to move the camera in four directions. The “Reset Angles” buttons resets the rotation and other related information of the model back to initial state. “Pause the app” and “Move to next task” buttons are two high level functions strictly used for running the user experiment. When users feel tired or fatigue during the tasks, they can press “Pause the app” to pause the entire application and the system will save the current status. Then users can press the same button to continue doing tasks and this will not affect the process of collecting data.

Lastly, the “+” and “-” buttons, and the slider bar provide operations for the layer-based exploded view process. When the “+” button is pressed, the system will explode next layer of objects and the “-” button executes the opposite function of the “+” button; it will make the previous layer’s (larger) objects appear and reset the current layer’s (smaller) objects to their initial position without exploding them. In other words, the whole process of exploding and resetting components’ position is analogous to peeling an onion from the outside layer to the inside and then unpeeling it from the inside layer to the outside.

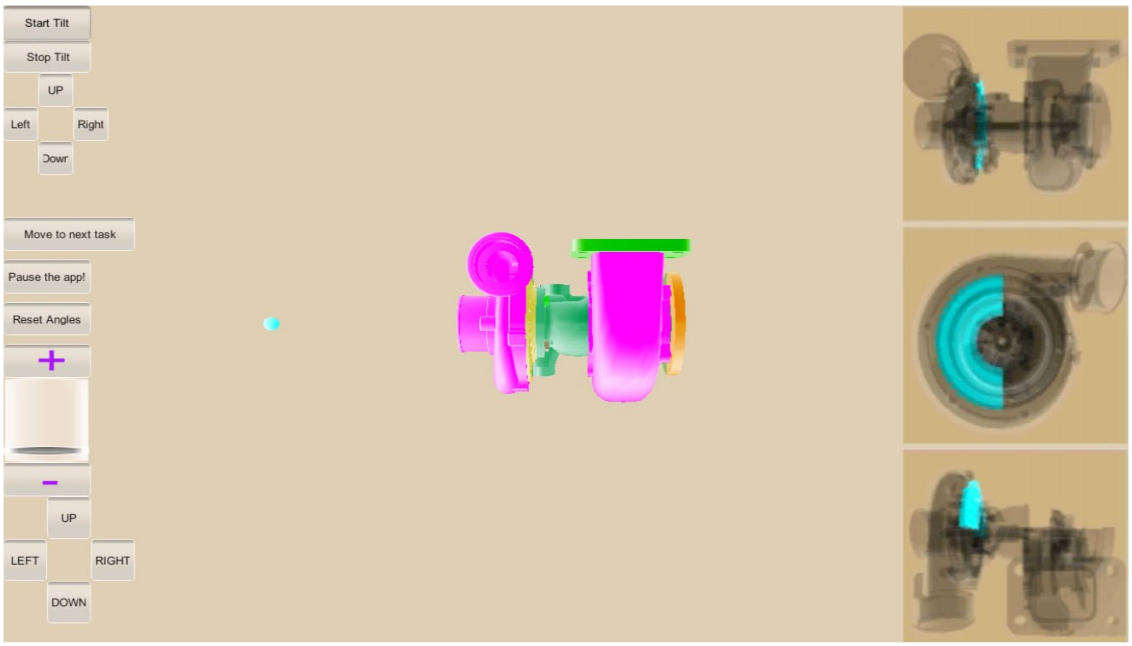


Figure 18: Overview Interface of Scale-based Exploded View.

Touch screen interactions mainly occur in the middle section of the interface. The system utilizes two finger pinching for zooming in and zooming out, where a pinch in moves the camera closer to the model and pinch out moves the camera farther away. The minimum and maximum distances between the camera and model are pre-defined by the system so the view stays within a reasonable scope, which means the position of model, probe and camera are fixed when they are first loaded into the system. The minimum and maximum values are an exposed variables which can be adjusted for the particular scene. The system also enables one finger dragging to move the probe on the screen when the finger touches the selection area of the probe, which is approximately the same size of an average finger’s touching area. The reason for expanding the selection region of the small probe is that we want to make sure it can be selected by "a fat finger" on a tablet as this will be discussed in the next sub-section. Alternatively, one finger sliding performs rotation of the model when the finger located within an empty area where no object is selected including components of model and 3D interactive probe.

The right section of the screen shows three views (left side, top down and front side) of the 3D structure which highlights the target object. These three pictures are pre-generated and statically placed at the right side. The purpose of these views is to provide users with three dimensional spatial information of the searching target, so they will have better sense of where the target object is within the model. The 3D model in the first scene shown in Figure 15 is presented with front side view and users can begin searching the highlighted target object by comparing it views at left. This view section is strictly for the user study experiments and would not be present in the actual application where we assume mechanics already acquire this knowledge from the real objects.

3.4 USE OF TRANSPARENCY

It is essential that users can keep track of the probe all the times since it is the main interactive tool of the system. The three dimensional environment makes the probe easily hidden behind the 3D objects in the scenes. To prevent this, we make all objects between finger and the probe semitransparent so that user can see the probe as shown in Figure 19. We can see from image that objects blocking the view of probe are rendered in semitransparent so that we can constantly keep track of the probe.

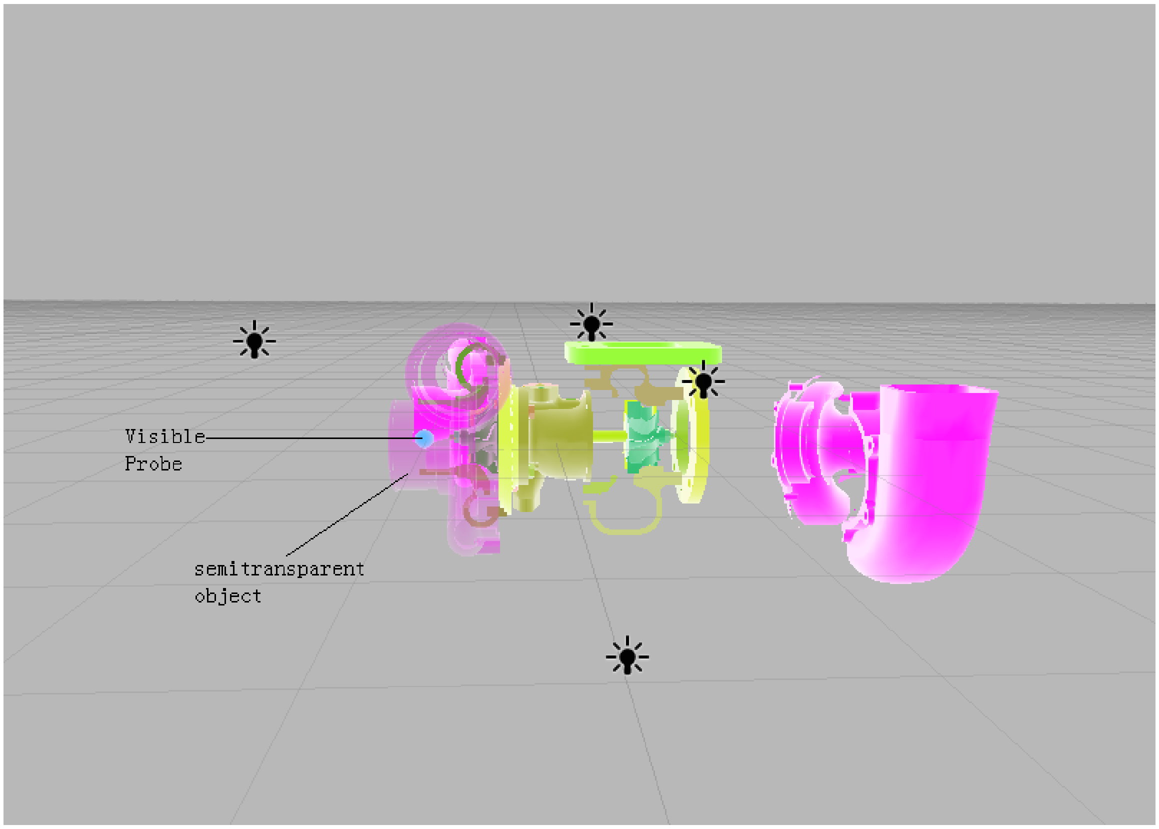


Figure 19: Semitransparent effect to ensure visibility of the probe.

3.5 THE EXPLODED VIEW ALGORITHM

The algorithm for pushing away each layer's objects from the probe is simple and cheap to compute. The order of time complexity of our approach is O(n) since the 3D probe interacts with only one component each time and do this in sequence. It is described in the following algorithm where P_{object} represents the position of an exploding object in 3D space, P_{probe} is the position of probe, P_{ini} is the initial position of the object when it is loaded to the scene, D_{ini} represents initial distance between the probe and object when the object first enters the sphere collider, D_{cur} is the distance between probe and P_{ini}, and V_{ini} represents a vector with length of D_{ini} and with a direction from the probe to the object. The pseudo-code of the simple method is shown below:

if $D_{cur} \le D_{ini}$ **then**

$$P_{object} = P_{probe} + V_{ini}$$

else

$$P_{object} = P_{ini}$$

end if

From the calculation above we can see that the 3D position of any object is determined by the position of the probe under the condition where $D_{cur} \le D_{ini}$. And when distance between probe and initial position D_{cur} is bigger than D_{ini}, the object returns to its initial position. The algorithm is applied to all objects within the current active layer in the model. This is concisely illustrated in Figure 20. The top row of the figure shows the probe outside the object's range, D_{ini}. The middle row shows the probe at the limit of the objects range with still no effect. The third row shows the push motion caused by the probe when within D_{ini}. The object is pushed away from the probe to maintain its distance from the probe.

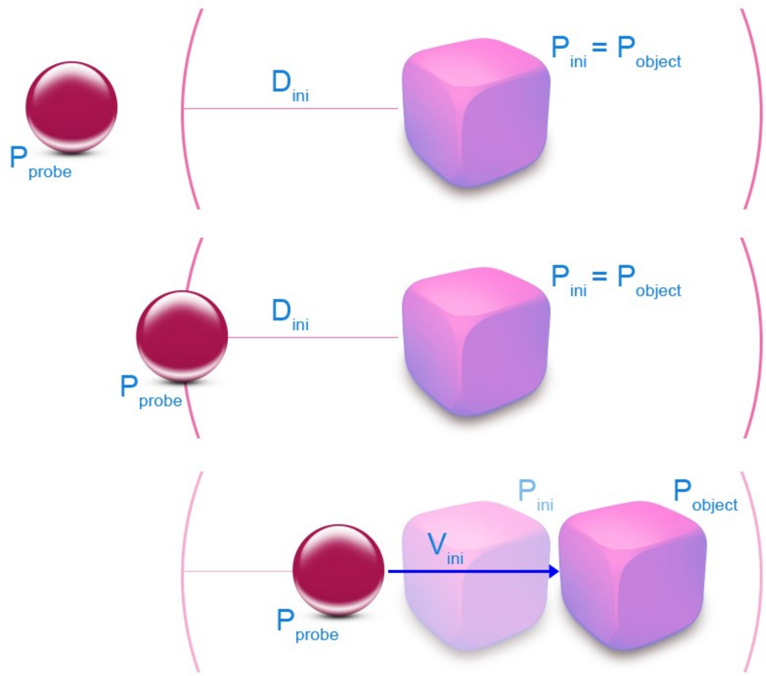


Figure 20: Illustration of the effect the probe on an object's position that is within the current active layer.

Two ArrayLists, ActiveObjects and InactiveObjects, are created for maintaining a list of exploding objects and static objects. When the "+" button is pressed by the user the next layer, L_{i+1}, of (smaller) objects which are ready for exploding are added to the ActiveObjects list. By operating the 3D probe, the user can manipulate the exploding objects towards any direction. When the "-" button is pressed, then the system will remove the current layer's L_i, set of exploding objects and add those objects to the InactiveObjects list. A brief pseudo code is shown below:

```
if ("+" is pressed ) then
{
        ActiveObjects.add (layer L_{i+1}).
        InactiveObjects.remove (layer L_{i+1}).
        ActiveObjects.remove (layer L_i).
        InactiveObjects.add (layer L_i).
}
If ("-" is pressed) then
{
        InactiveObjects.add (layer L_i).
        ActiveObjects.remove (layer L_i)
        ActiveObjects.add (layer L_{i-1}).
        InactiveObjects.remove (layer L_{i-1})
}
```

At any time the total number of objects within 3D model is the sum of objects in InactiveObjects list and ActiveObjects list. Objects in ActiveList are currently available for exploding and objects in InactiveObjects list maintain their original position.

CHAPTER 4 USER STUDY

Since our research is part of a larger project which aims to improve the efficiency of mechanical engineers while carrying out maintenance and repair operations, the effectiveness and error rates are key factors we wish to evaluate in our experiment. In order to evaluate the overall performance of the scale-based explosion technique (SBET), we conducted a controlled user study comparing our method with an alternate exploded view based selection approach. This alternate whole explosion (WE) technique simply explodes every component of the 3D model at one time (as shown in Figure 21), and does not constrain the dispersion of components to layers of a particular size. The implemented WE technique is a simplified method, which applies the idea from Li at al [23]. The interface of WE is the same as interface of SBET only without "+", "-" buttons and associated slider bar for controlling layer-based explosion. As discussed in the prior work section, their system calculates the relationship between each component and exploded objects based on the rule that components should not pass through each other. However, their approach is computationally expensive, not only on the CPU but also on of the GPU ofdesktop machines. Mobile device cannot support such complex algorithms. Therefore, we used a simplified algorithm of SBET and applied 3D explosion as described above for all parts of the model regardless of size. The underlying algorithms between two methods are the same, however SBET uses layer-based explosion while WE applies explosion technique without considering the layer. We chose this method as it would also be feasible for use on mobile devices as it is computationally inexpensive. Our aim is begin to establish benchmarks for interaction performance of exploded view techniques that are tractable on mobile devices.

Figure 21: Comparison of two exploded view techniques: WE (Left) and SBET (Right).

4.1 RESEARCH QUESTIONS

As discussed earlier in the introduction section, the goal of our research is to provide better solutions to improve the efficiency of workers engaged in assembly tasks. Finding broken parts that are small and occlude is one of common tasks conducted by mechanical engineers in their repairing operations. By conducting a user study, we want to validate research hypotheses as follows:

- The scale-based exploded view technique (SBET) performs better than whole model exploded view technique (WE) at finding small and occluded parts with 3D models, in terms of both time required and accuracy.
- The complexity of 3D models and the size of the searched target affect the performance of a scale-based exploded view technique.

4.2 INITIAL STUDY DESIGN

As we did not have access to real aircraft mechanic population and their environment, we created a series of tasks to imitate the actual operations by such mechanics. The goal of this study is to compare the effectiveness between two different low cost exploded view techniques for finding and selecting small and occluded objects in 3D virtual models on mobile devices. Hence, we categorized the measurement into three dependent variables which are: technique, complexity and target size.

We designed a 2x3x3 within-subject study, with selection technique (SBET, WE), complexity (1: 150 parts, 2: 300 parts, 3: 450 parts) and target size (1: large, 2: medium, 3: small). Different target sizes and different complexity of models are shown in Appendix J. We wanted to measure how the complexity and size of the target affect the performance of SBET as we stated in research question 2. So we selected levels for independent variables that represent a range of target size and model complexity. Table 1 presents number of triangles and verticals of each model and their related frame rates on the system. Each task concerns the finding of a certain size object within a model on a mobile device and each participant performs all 18 tasks as shown in Table 2.

Table 1: Basic triangles and verticals information of three models and frame rates.

Model Complexity	Number of Triangles	Number of Verticals	Frame Rates (FPS)
150 Parts	101, 400	83,000	200 FPS
300 Parts	306,500	275,500	67 FPS
450 Parts	510,200	377,000	36 FPS

The device we used for this study is an Acer A510 Tablet with a 1280 X 800 resolution powered by Android 4.1. All three models were downloaded from the Grabcad [32] [33] [34] free CAD library website. The models all belong to the solid model category and have internal structures which are made of small objects using triangles and verticals. We used one model with 50 parts for the training tasks and three other models for the actual user study which has 150 parts, 300 parts and 450 parts respectively, as shown in Appendix I. Each model has a different number of parts which represents the complexity level. For example, model 1, which has 150 parts constructing the entire model, belongs to model complexity level 1. The reason we picked these models is that all these models are either virtual engines or turbo which are common components found the target industries. Additionally, we tested larger models in our system and found that models with more than 450 components are difficult to renderer and run on mobile devices.

Table 2: 18 Designed tasks for each participant.

Task #	3 Model Complexities	3 Target Sizes	2 Explosion Methods
1	1	1	1
2	1	2	1
3	1	3	1
4	2	1	1
5	2	2	1
6	2	3	1
7	3	1	1
8	3	2	1
9	3	3	1
10	1	1	2
11	1	2	2
12	1	3	2
13	2	1	2
14	2	2	2
15	2	3	2
16	3	1	2
17	3	2	2
18	3	3	2

4.3 PILOT STUDY

In order to formulate and refine our formal user study, we conducted a pilot study with 8 participants who were mainly students at Dalhousie University. Each participant performed the 18 tasks which varied by the complexity of the model (three levels), size of the target (three levels) and different explosion techniques (two levels). All participants performed repeated measures using the two different techniques, however the sequence of the technique used to do the tasks are different. Four of them used SBET first and then used WE to perform the same 9 tasks, while the other four used WE first and then finish the same task with SBET.

As we can see from Table 3, whichever technique was used first took longer than the second, participants who used either technique in the first place spent more time than participants who previously finished the same tasks using another technique and the difference is significant. This indicates that participants learned about the task itself and we need to counterbalance learning effects in our experiments. Another aspect we learned from the pilot study is that we need to control the difficulty of the tasks. For example, 6 out of 8 pilot participants could not find the target object in task 9 and 18, which have extremely small targets. We needed make our smallest target object larger so that participants are able to find it within reasonable time. In addition, we realized that participants are confused with the concept of "layer" within the context of a 3D model and we decided to render the same layer objects with same color so that users can distinguish those objects instantly know which layer of objects is exploding.

Table 3: Average task finishing time using different orders of explosion techniques.

Experiment Sequence with explosion technique	First Time	Second Time	Average
SBET	1206s	1090s	1148s
WE	1432s	1037s	1235s

4.4 FINAL STUDY DESIGN

As a result of the pilot study, we made the following changes in our study design.

The first change we made was based on the learning effect we observed in our pilot study (Section 4.3), where we performed repeated measures on 8 participants and the results showed that there was a large learning factor involved in the task. Therefore, we separated the two exploding techniques and tested them as a between subject variable and designed 2x3x3 mixed design, with selection technique (SEBT, WE) as the between subjects variable and complexity (1: 150 parts, 2: 300 parts, 3: 450 parts) and target size (1: large, 2: medium, 3: small) as within subject variables. Each participant only needs to perform 9 tasks that varied in complexity and target size using only one technique as shown in Table 4.

Table 4: User study tasks based on model complexity and target size

	Large Target	Medium Target	Small Target
Model with 150 Parts	Task 1	Task 2	Task 3
Model with 300 Parts	Task 4	Task 5	Task 6
Model with 450 Parts	Task 7	Task 8	Task 9

The second change we made is to make some tasks easier which means making some of the potential target objects larger so that participants can retrieve it within the limited time of the study.

The third change we made was based on the complaint that participants were confused about the concept of layer and related objects in that layer. In order to distinguish the same layer objects from the rest of the components of the 3D model, we rendered the currently exploding objects with same color so that participants can easily know which objects are exploding at the moment.

After making changes to our study design, we piloted another study of 4 participants to make sure the changes worked. The rest of study design is mostly the same as our initial design as each participant needs to find a certain small and occluded object within different 3D models on the tablet device.

4.4.1 Study Tasks and Protocols

In order to mimic the mechanic's procedure of finding and selecting parts of 3D models, we provided participants with three different pictures which showed the target objects from three different angles as described in the 3.1 Interface section. This provides the user with a sense of the spatial location of the target components within the overall 3D structure. A real mechanic would likewise have a good sense of where the object is within the overall structure from direct observation.

Before participants engaged in the study tasks, we trained them with 4 training tasks to allow them to become familiar with the interface and techniques. The training process is identical to the actual user task except with an easier model and fewer tasks. For each participant, we used the same training 3D model regardless of the exploded view method they used.

All participants involved in the study signed an informed consent form [see Appendix C], which explained the detail of the study and other aspects they may encounter during the study including minor fatigue, frustration, the participants' right to withdraw from the study without consequence, compensation [see Appendix H] and assurance of confidentiality and anonymity of personal data. After the training session, participants filled out a background questionnaire and then they were given 9 tasks [see Appendix J] using only one of the two exploded view methods under testing.

4.4.2 Participants Recruitment

We recruited 36 students from the Dalhousie University campus through different methods including Notice Digest, the Computer Science Mailing List, the Dal Student Email lists and physical bulletin boards. The email announcement is given in Appendix A and poster recruitment is given in Appendix B. We also sent a screening email (Appendix C) to ensure that the participant met the inclusion criteria (English fluency and experience with touch screen devices). English fluency is necessary because all of our resources including the prototype application and paper materials are in English. In addition, participants should have basic experience with touch devices since our experiment is carried out on android tablet and requires interactions on a touch screen.

4.4.3 Counterbalance Measure

In order to counterbalance the conditions in the experiment, we used Balanced Latin Squares [36] to arrange the sequence in which our participants take the study, as shown in Table 5. Although the optimal way of reducing the carryover effects would be to do a full 9 factorial permutation, this would be infeasible as it would require 362,880 participants. Participant number is a sequence number we gave to each participant. For example, P1 means the first participant, P3 means the third participant, and etc. Technique types represent which technique is used to perform tasks during the study. Task number marks each individual task as shown in Table 4.

Table 5: Balanced Latin Square for user study

Participant Number	Technique Types	Orde r #	Task Numbers (complexities x sizes)								
P1, P19	SBET	1	1	2	9	3	8	4	7	5	6
P2, P20	WE		1	2	9	3	8	4	7	5	6
P3, P21	SBET	2	2	3	1	4	9	5	8	6	7
P4, P22	WE		2	3	1	4	9	5	8	6	7
P5, P23	SBET	3	3	4	2	5	1	6	9	7	8
P6, P24	WE		3	4	2	5	1	6	9	7	8
P7, P25	SBET	4	4	5	3	6	2	7	1	8	9
P8, P26	WE		4	5	3	6	2	7	1	8	9
P9, P27	SBET	5	5	6	4	7	3	8	2	9	1
P10, P28	WE		5	6	4	7	3	8	2	9	1
P11, P29	SBET	6	6	7	5	8	4	9	3	1	2
P12, P30	WE		6	7	5	8	4	9	3	1	2
P13, P31	SBET	7	7	8	6	9	5	1	4	2	3
P14, P32	WE		7	8	6	9	5	1	4	2	3
P15, P33	SBET	8	8	9	7	1	6	2	5	3	4
P16, P34	WE		8	9	7	1	6	2	5	3	4
P17, P35	SBET	9	9	1	8	2	7	3	6	4	5
P18, P36	WE		9	1	8	2	7	3	6	4	5

4.4.4 Data Collection

We recorded the timings of participants' attempts at finding and selecting a target object, and the number of errors they made during this process. The number of errors are defined as when participants mistakenly select objects that are not the target objects. These two aspects comprised our objective quantitative measures of performance. Also, participants logged into the system and the application recorded the tracks of fingers on touchscreen to obtain detailed knowledge about how participants interact with 3D models on mobile devices and where they might be having difficulty (errors in selection, difficulties switching modes, etc.). After finishing all 9 tasks, participants were given a 5 minutes break and then they filled out the post-task questionnaires after the session [see Appendix F] in order to provide subjective quantitative data such as the degree of user satisfaction with the interface and confidence about finishing tasks. We also audio recorded post-session interviews [see Appendix G] to obtain additional feedbacks, which might not be apparent in the previous data and help us to more comprehensively understand the preference of a participant in terms of the two exploded view techniques.

4.5 STUDY RESULTS

As discussed previously, our log system recorded each participant's number of probe movements, task finishing time, wrong target selection times and number of camera rotations. After finishing all 9 tasks, participants also filled out the questionnaire and answered interview questions. We had three independent variables and four dependent variables as shown below.

Independent variables:

- Model Complexity with three levels: level 1 = 150 components, level 2 = 300 components, level 3 = 450 components.
- Target Size with three levels: level 1 = large, level 2 = medium, level 3 = small.
- Techniques: SBET (Scale-based Explosion Technique) and WE (Whole Explosion)

Dependent variables:

- Probe movement times, camera rotation times, task finishing time and wrong target selection times.

4.5.1 Task Finishing Time

Task finishing time is defined as the time from when the participant started touching the screen to the final selection of the correct target. Table 6 shows the descriptive statistical results of task finishing time over the three different complexity of models, three different target sizes and two different selection methods.

Table 6: Descriptive statistics of task finishing time in seconds.

	Tech	Mean	Std. Deviation	N
Target Size = Large, Model Complexity = 150 parts	SBET	40.3406	35.89987	18
	WE	35.8611	37.03488	18
	Total	38.1008	36.01869	36
Target Size = Medium, Model Complexity = 150 parts	SBET	84.1417	57.10377	18
	WE	50.4189	41.78973	18
	Total	67.2803	52.19683	36
Target Size = Small, Model Complexity = 150 parts	SBET	102.0994	72.41021	18
	WE	112.9439	129.03573	18
	Total	107.5217	103.26764	36
Target Size = Large, Model Complexity = 300 parts	SBET	133.3367	67.43732	18
	WE	136.1689	120.68347	18
	Total	134.7528	96.35962	36
Target Size = Medium, Model Complexity = 300 parts	SBET	88.1183	39.70265	18
	WE	62.9178	51.29243	18
	Total	75.5181	46.97667	36
Target Size = Small, Model Complexity = 300 parts	SBET	164.9772	89.49968	18
	WE	160.6206	88.70041	18
	Total	162.7989	87.84663	36
Target Size = Large, Model Complexity = 450 parts	SBET	77.4511	42.47282	18
	WE	62.7411	54.55613	18
	Total	70.0961	48.75969	36
Target Size = Medium, Model Complexity = 450 parts	SBET	133.9872	82.93067	18
	WE	185.6356	129.12197	18
	Total	159.8114	110.11132	36
Target Size = Small, Model Complexity = 450 parts	SBET	205.3017	122.04178	18
	WE	293.5972	195.58844	18
	Total	249.4494	166.79316	36

Figure 22 is the plot for the two-way interaction between target size and method. Looking at the graph we can see that participants spent similar amount of time when target size equals 1 and 2, indicating that there is no method effect when the target size is not small.

However, participants spent much more time when the target size equals 3 using WE than using SBET, indicating that there might be method effect when target becomes very small.

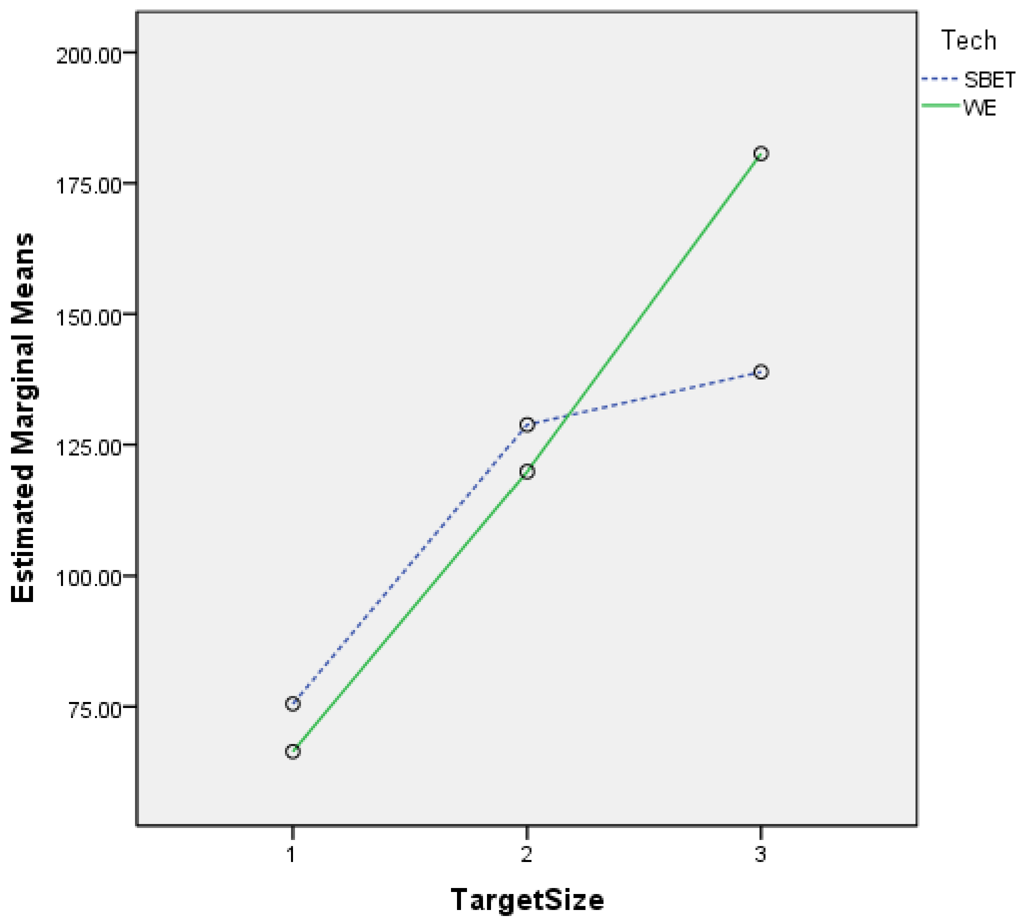


Figure 22: Interactions between tech and target size on task finishing time were found to be significant. (Target Size 1 = Large, 2 = Medium, 3 = Small)

Figure 23 illustrates interactions between method and model complexity across task finishing time. As seen from the graph, there is no method effect when model complexity equals 1 and 2. However, it seems that method becomes important effect when model gets more complex. The interaction effect between TargetSize and Method was found to be significant (P-value = 0.04), giving a further reason that there were different changes in the finishing time over two different selecting methods. Moreover, method showed as a simple main effect as participants using SBET (M = 115s) spent less time in genera than participants using WE (M = 123s).

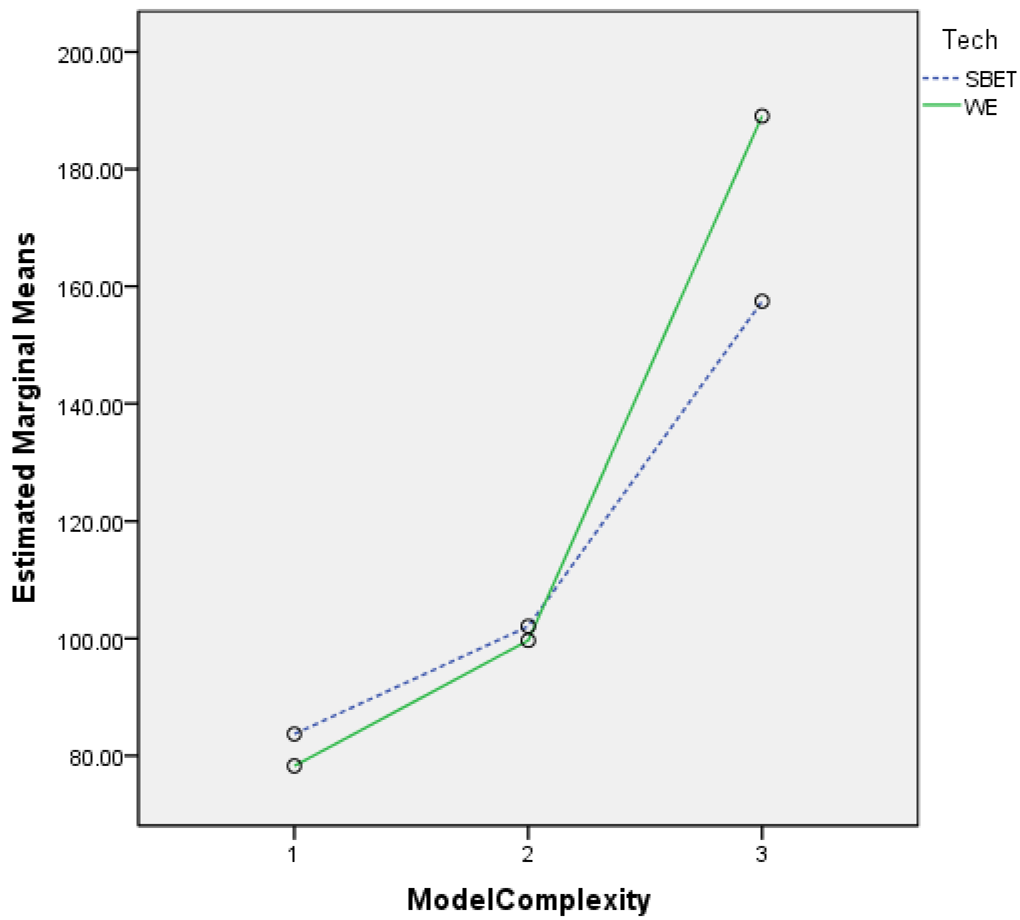


Figure 23: Interactions between model complexity and tech on task finishing time were found not significant (Model Complexity 1 = 150 parts, 2 = 300 parts, 3 = 450 parts).

Figure 24 illustrates the mean task finishing time of all participants combined with all three variables: complexity of model, size of searching target and method. The interaction effects between model complexity and method was found to be not significant (P-value = 0.265).

As expected, when the complexity of the model increases, more time is required to finish tasks and this applies to both techniques. However, there was one case that did not fit the general trend: complexity 2 and target size 1. Upon further investigation we found that the target was located in the center of model and the color of the target object was confused with the surrounding components. In addition, we can also point out that the average task finishing time increases as the size of target gets smaller and this also applies to both methods.

In addition, the graph tells us that average task completion time at complexity 1 and 2 were almost the same between two different techniques which means the method factor did not significantly impact the time to completion. However, as the model gets more complex and the target objects gets smaller, the difference of completion times between two methods increases significantly. In other words, our method showed a strong performance gain when the model becomes more complex and the target becomes small, which is our initial goal of this study.

We analyzed the result with split-plot ANOVA to see if any factor had significant effects on the average task finishing time. The results showed there were statistically significant main effects for complexity and target size ($F1 = 18.30$, $P1 < .0005$; $F2 = 37.23$, $P2 < .0005$) since our P-values for both methods were less than .05. Also, according to the Partial Eta Squared [35], the value obtained for complexity and target size were .526 and .693 respectively, which suggested a very large effect size (.01= small effect, .06 = moderate effect, .14 = large effect). As expected, the target size and model complexity factors greatly influenced the performance of both two approaches.

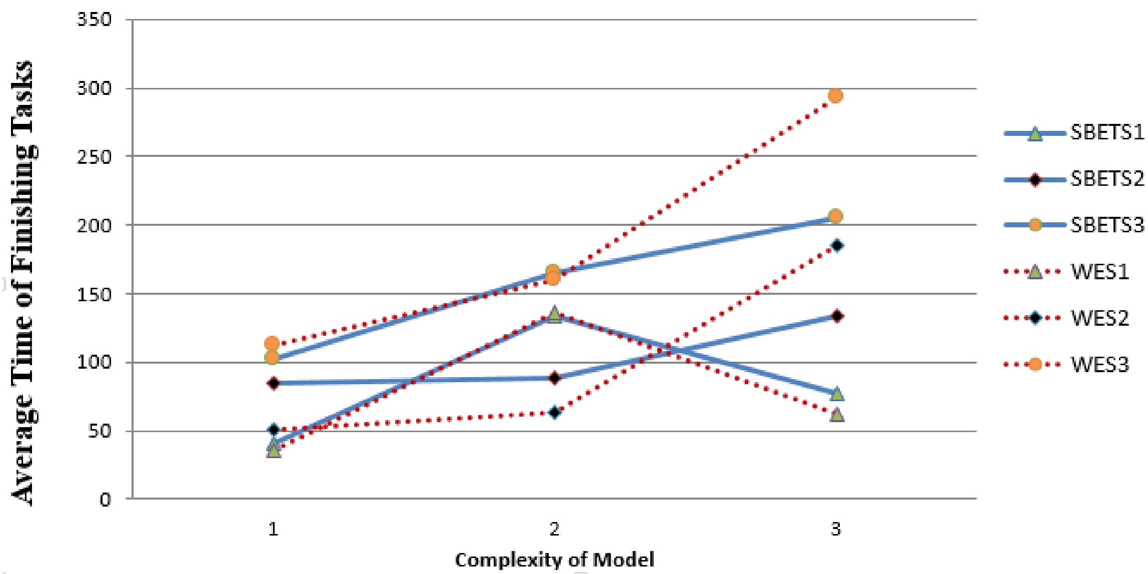


Figure 24: Average task finishing time combined with methods, target sizes and model complexity. SBETS1 stands for Scale-based Explosion Technique combined with Size 1 target and WES1 stands for Whole Explosion with target Size 1.

4.5.2 Number of Wrong Targets

The number of wrong targets is defined as the number of instances when participants mistakenly select objects that are not the target. Table 7 shows overall description statistics of wrong target selection over the three different target sizes, three different models and two different techniques.

Table 7: Descriptive statistics of wrong target selection times.

	Tech	Mean	Std. Deviation	N
Target Size = Large, Model Complexity = 150 parts	SBET	.78	1.060	18
	WE	1.44	2.202	18
	Total	1.11	1.737	36
Target Size = Medium, Model Complexity = 150 parts	SBET	1.44	1.756	18
	WE	2.89	4.702	18
	Total	2.17	3.574	36
Target Size = Small, Model Complexity = 150 parts	SBET	3.94	5.150	18
	WE	6.89	9.875	18
	Total	5.42	7.904	36
Target Size = Large, Model Complexity = 300 parts	SBET	.61	1.290	18
	WE	3.56	4.706	18
	Total	2.08	3.714	36
Target Size = Medium, Model Complexity = 300 parts	SBET	.61	1.650	18
	WE	1.22	2.625	18
	Total	.92	2.183	36
Target Size = Small, Model Complexity = 300 parts	SBET	4.28	3.064	18
	WE	8.39	9.413	18
	Total	6.33	7.207	36
Target Size = Large, Model Complexity = 450 parts	SBET	.56	.511	18
	WE	1.50	1.855	18
	Total	1.03	1.424	36
Target Size = Medium, Model Complexity = 450 parts	SBET	3.94	9.938	18
	WE	5.06	5.070	18
	Total	4.50	7.796	36
Target Size = Small, Model Complexity = 450 parts	SBET	3.94	4.304	18
	WE	13.94	14.136	18
	Total	8.94	11.479	36

Figure 25 and 26 shows interactions effect of both TargetSize X Tech and ModelComplexity X Tech and there were no significance found in either of these two interactions (P1 = 0.491, P = 0.131). Also 3-way interaction TargetSize X ModelComplexity X Tech on number of wrong targets was found to be not significant.

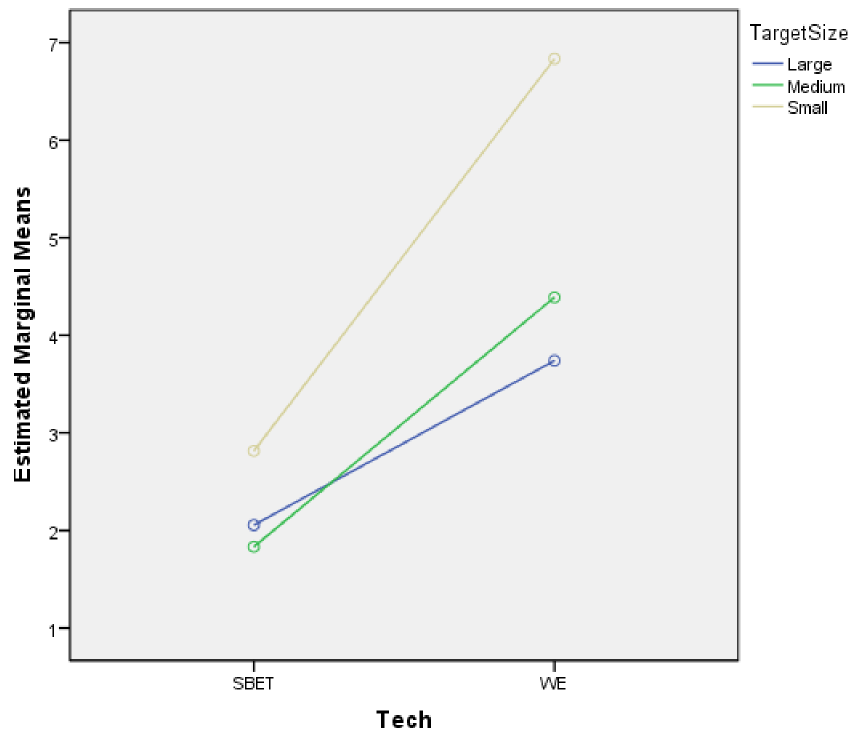


Figure 25: Interactions between target size and techniques on number of wrong targets were found not significant.

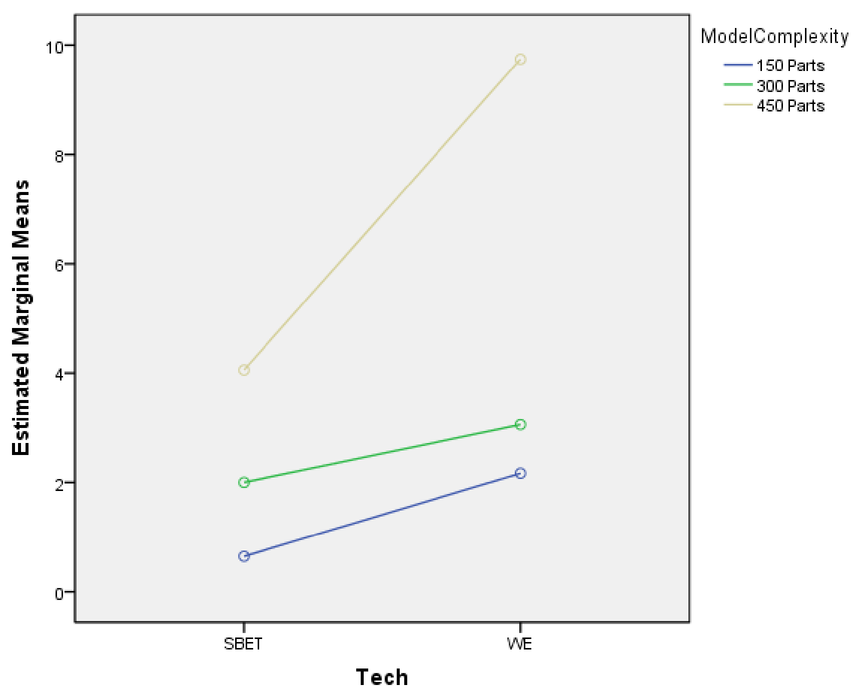


Figure 26: Interactions between model complexity and techniques on number of wrong targets were found not significant.

As we can see from Figure 26 that as the complexity of the model increases, the average number of selected wrong targets increases as well for both techniques except one case of target size 1 at complexity level 2. As discussed, the same reason also applies here which is that the target object is centered in the 3D model and the surrounding objects' colors are very similar to the color of the target components. This could increase the possibility of the choosing the wrong target because participants may confuse the target with parts that are surrounding it.

We can also see from Figure 27 that as the size of the target gets smaller, participants tend to select more wrong targets when they use the WE technique. However, participants selected approximately an equal amount of wrong targets across all the levels of complexities and sizes when they used SBET. Another result shown in this graph is that when the complexity increases, the gap between two different techniques at different target sizes increases in terms of wrong target selection.

By analyzing the final result with mixed ANOVA, we found out that there was no significant difference on model complexity ($F = 2.727$, $P = 0.08$) since its p value was greater than .05. But there was significant difference on target size ($F = 12.558$, $P < .0005$) which was smaller than p value .05. So target size had an effect on wrong target selection. As we described before, the effect size was large according to the Partial Eta Squared [35] value which was .432 greater than .14 on target size.

There was also a statistically significant difference between the two techniques in the average number of wrong targets selection since the p value was smaller than .05 ($F = 11.621$, $P = .002$). This means that participants using SBET selected fewer wrong targets than participants using WE. Also, the effect size was very large (.01= small effect, .06 = moderate effect, .14 = large effect).

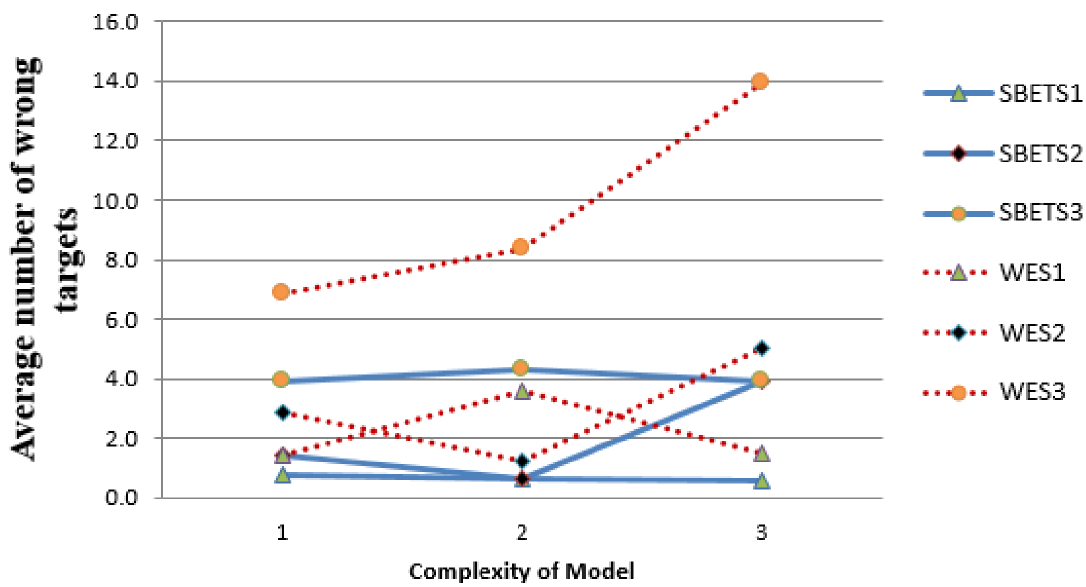


Figure 27: Average number of wrong target selections combined with methods, target sizes and model complexity.

4.5.3 Number of Probe Movements Analysis

Probe movement is defined as how many times the probes were moved by participants during the task. Table 8 shows average probe movement times over the different complexities, different sizes and different methods.

Table 8 : Descriptive statistics of probe movement times.

	Tech	Mean	Std. Deviation	N
Target Size = Large, Model Complexity = 150 parts	SBET	2.89	2.423	18
	WE	2.56	2.121	18
	Total	2.72	2.250	36
Target Size = Medium, Model Complexity = 150 parts	SBET	7.17	5.659	18
	WE	3.61	3.090	18
	Total	5.39	4.842	36
Target Size = Small, Model Complexity = 150 parts	SBET	5.78	5.397	18
	WE	6.50	7.262	18
	Total	6.14	6.316	36
Target Size = Large, Model Complexity = 300 parts	SBET	8.89	5.212	18
	WE	7.39	7.648	18
	Total	8.14	6.495	36
Target Size = Medium, Model Complexity = 300 parts	SBET	8.44	4.630	18
	WE	4.28	5.454	18
	Total	6.36	5.415	36
Target Size = Small, Model Complexity = 300 parts	SBET	12.83	9.679	18
	WE	9.56	6.289	18
	Total	11.19	8.214	36
Target Size = Large, Model Complexity = 450 parts	SBET	8.39	5.248	18
	WE	4.78	4.821	18
	Total	6.58	5.294	36
Target Size = Medium, Model Complexity = 450 parts	SBET	8.17	5.501	18
	WE	8.78	7.848	18
	Total	8.47	6.687	36
Target Size = Small, Model Complexity = 450 parts	SBET	11.44	11.268	18
	WE	14.50	12.477	18
	Total	12.97	11.819	36

Figure 28 shows the interaction between two of the independent variables: technique and model complexity. As seen from the Figure, there are similar changes in the probe movement times for the two different techniques over three different model complexities. The P-value of Tech X ModelComplexity were 0.330 (P-values > 0.05 indicates no significant difference, otherwise it shows that the factor indicates significant difference), meaning that the interaction effect between technique and model complexity is not statistically significant.

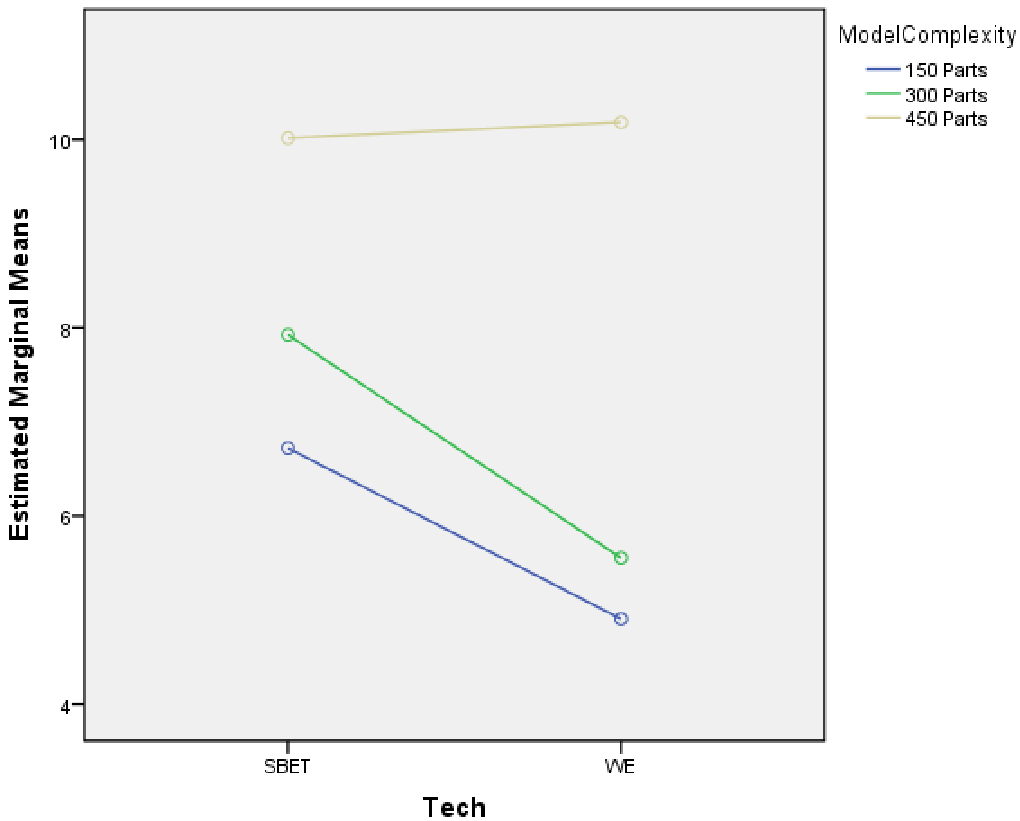


Figure 28: Interactions between model complexity and technique on number of probe movements were not found to be significant.

Figure 29 shows interactions between two dependent variables: technique and target size. The P-value of Tech X TargetSize was 0.307, which indicated no significant differences. Additionally, the P-value of Tech X ModelComplexity X TargeSize was 0.286 also indicated no significant differences.

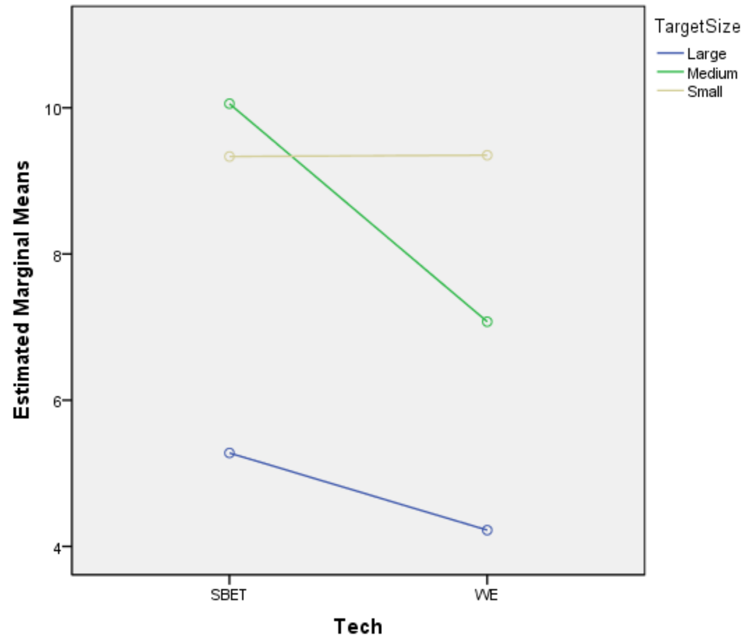


Figure 29: Interactions between target size and technique on number of wrong targets were not found to be significant.

Although there were no 3-way and 2-way interactions, the main effect for target size and model complexity are significant. (P-value < 0.005). As the target gets smaller or the model gets more complex, participants performed more probe movements in the tasks as illustrated in Figure 30 and Figure 31. Moreover, the main effect for the different techniques is not significant on the probe movement times (P-value = 0.273).

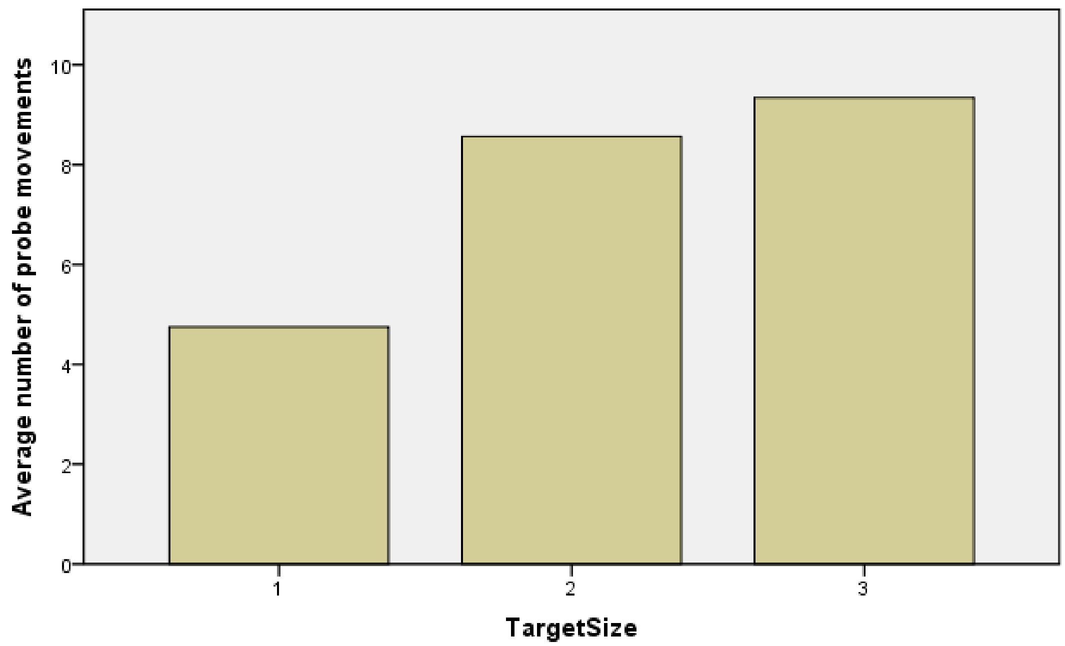


Figure 30: Main effect for target size over number of probe movements.

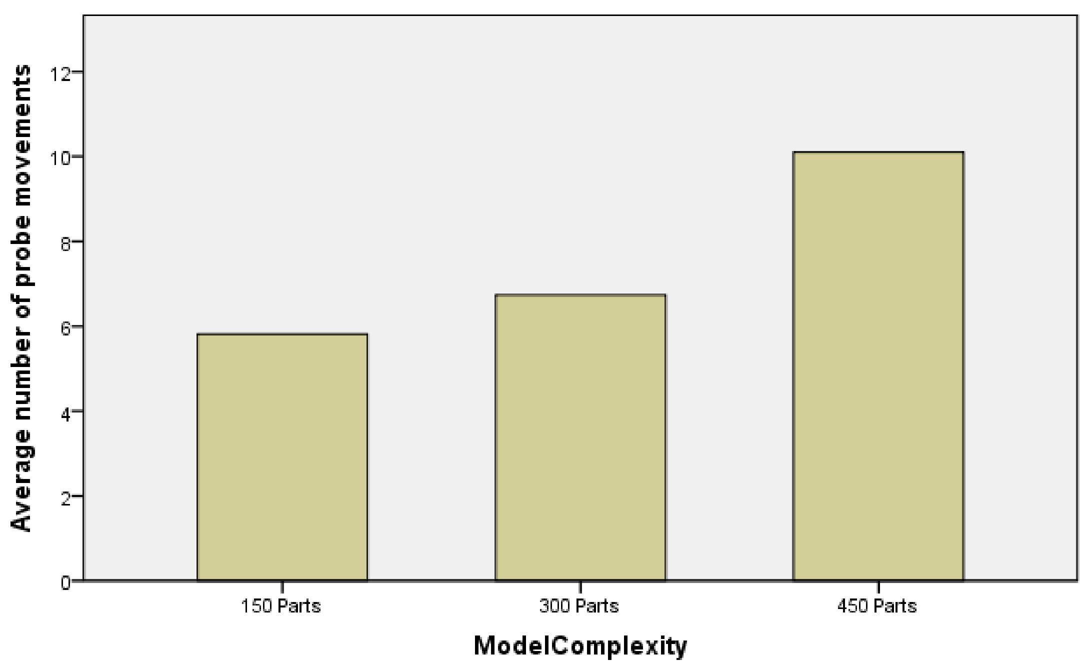


Figure 31: Main effect for model complexity over number of probe movements.

4.5.4 Number of Camera Rotations Analysis

The number of camera rotations for finding the correct target are also recorded in the system's log file and this defines as the number of times participants used swipe gesture to rotate the virtual camera in 3D scene. Table 9 shows the mean values of camera rotation times over different complexity, different target sizes, and different techniques.

Table 9: Descriptive statistics of camera rotation times.

	Tech	Mean	Std. Deviation	N
Target Size = Large, Model Complexity = 150 parts	SBET	10.39	8.479	18
	WE	13.94	13.807	18
	Total	12.17	11.436	36
Target Size = Medium, Model Complexity = 150 parts	SBET	19.28	11.002	18
	WE	14.50	11.325	18
	Total	16.89	11.268	36
Target Size = Small, Model Complexity = 150 parts	SBET	23.17	19.018	18
	WE	29.83	34.765	18
	Total	26.50	27.823	36
Target Size = Large, Model Complexity = 300 parts	SBET	21.11	15.289	18
	WE	32.44	41.442	18
	Total	26.78	31.317	36
Target Size = Medium, Model Complexity = 300 parts	SBET	11.11	9.474	18
	WE	8.56	7.350	18
	Total	9.83	8.457	36
Target Size = Small, Model Complexity = 300 parts	SBET	15.83	16.005	18
	WE	22.83	19.675	18
	Total	19.33	18.029	36
Target Size = Large, Model Complexity = 450 parts	SBET	5.11	5.759	18
	WE	7.39	7.261	18
	Total	6.25	6.561	36
Target Size = Medium, Model Complexity = 450 parts	SBET	18.78	15.743	18
	WE	31.00	29.029	18
	Total	24.89	23.835	36
Target Size = Small, Model Complexity = 450 parts	SBET	21.50	21.192	18
	WE	35.56	29.772	18
	Total	28.53	26.447	36

Figure 32 and Figure 33 shows the 2-way interactions: Tech X Model Complexity (Figure 32) and Tech X Target Size (Figure 33). No significant effect on either of these two interactions was found: Tech X ModelComplexity (P = 0.406) and Tech X TargetSize (P = 0.230). Both graph illustrates that participants tended to make the same camera rotation times when the model is complex (ModelComplexity level = 3) and the target is small (target size level = 3).

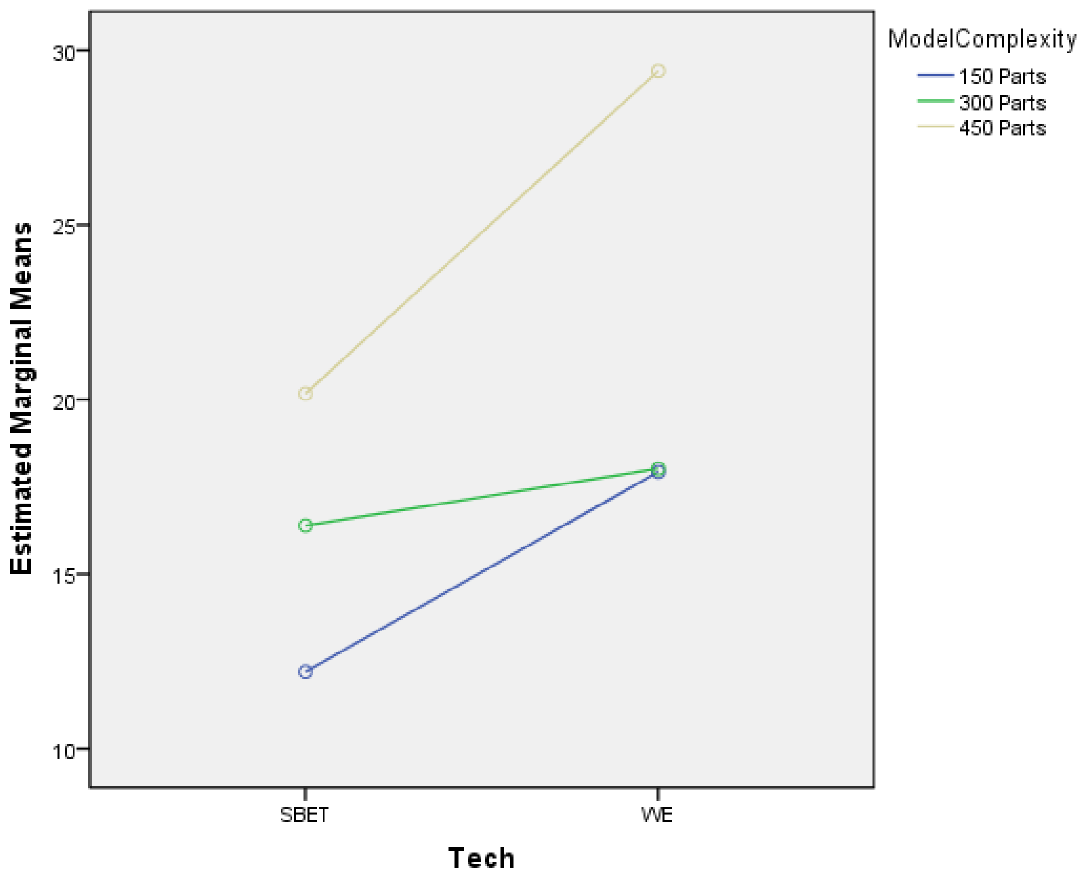


Figure 32: Interactions between technique and model complexity on number of camera rotations were not found to be significant.

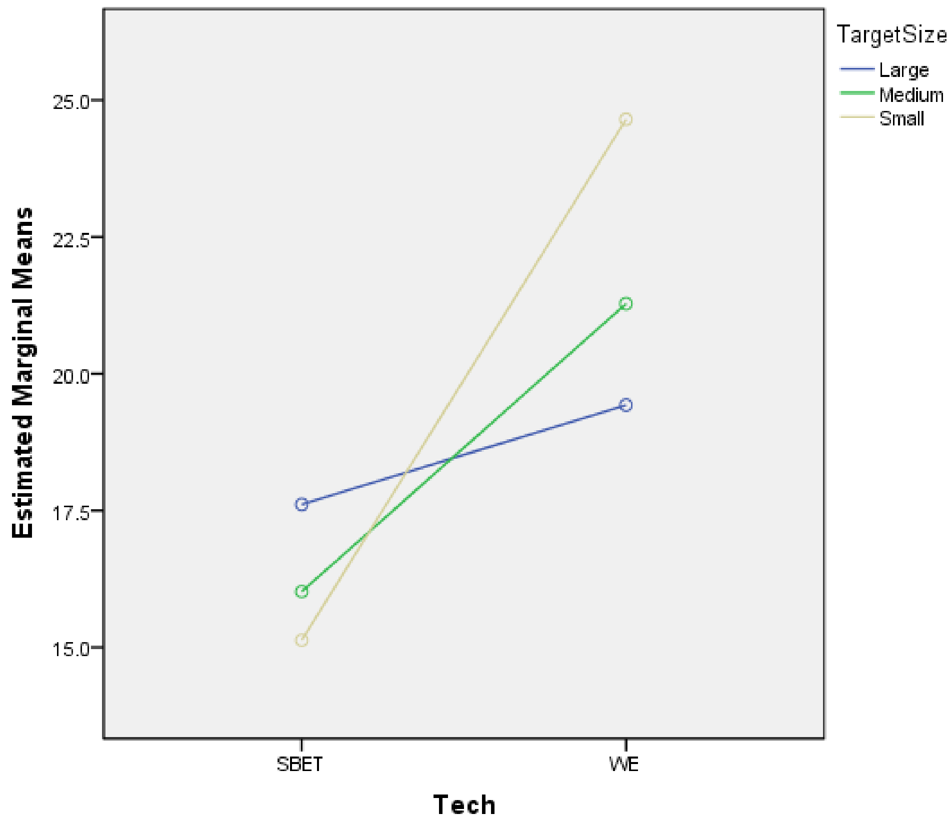


Figure 33: Interactions between technique and target size on number of camera rotations were not found to be significant.

The main effects for the model complexity was statistically significant (P1< 0.005), while there was no significant difference found on the target size (P-value = 0.825). As the model gets more complex, participants performed more number of camera rotations as illustrate in Figure 34. Also, the main effect for different techniques was not significant (P-value = 0.132), indicating that there was no significant difference in the number of camera rotations for the two techniques (SBET and WE).

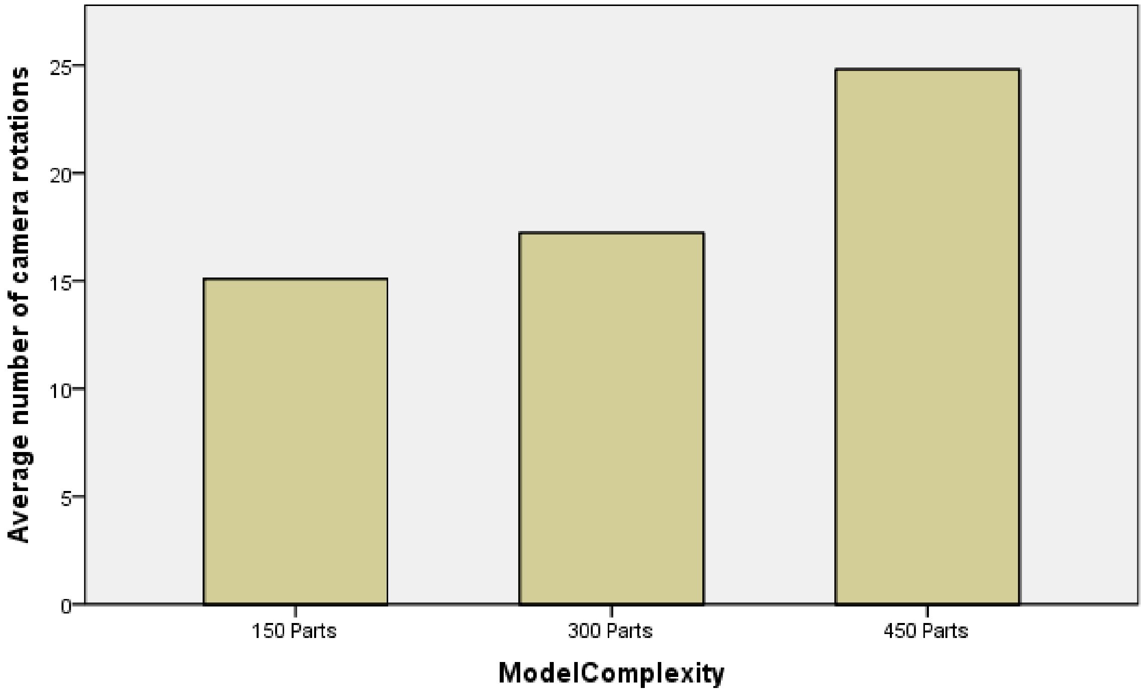


Figure 34: Main effect of model complexity on number of camera rotations.

4.5.5 Questionnaire

We administered a questionnaire after participants finished all 9 tasks. We asked participants to evaluate the technique they used in terms of the interface and system responsiveness, as well as other aspects. The results are shown in Figures 35-43.

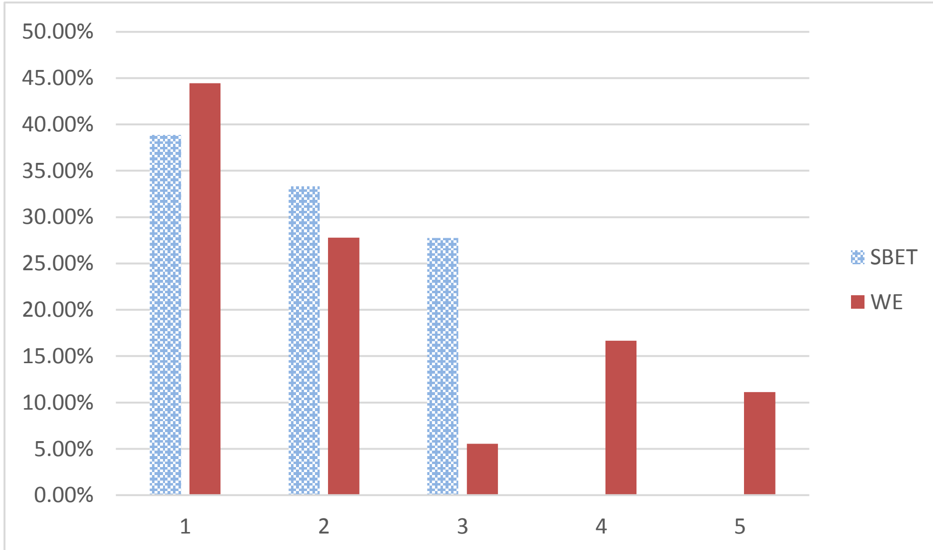


Figure 35: SBET and WE comparison for question 1 (“The interface of application is easy to understand. – 1. Strongly Agree, 2. Somewhat Agree, 3. Neutral, 4. Somewhat Disagree, 5. Strongly Disagree”).

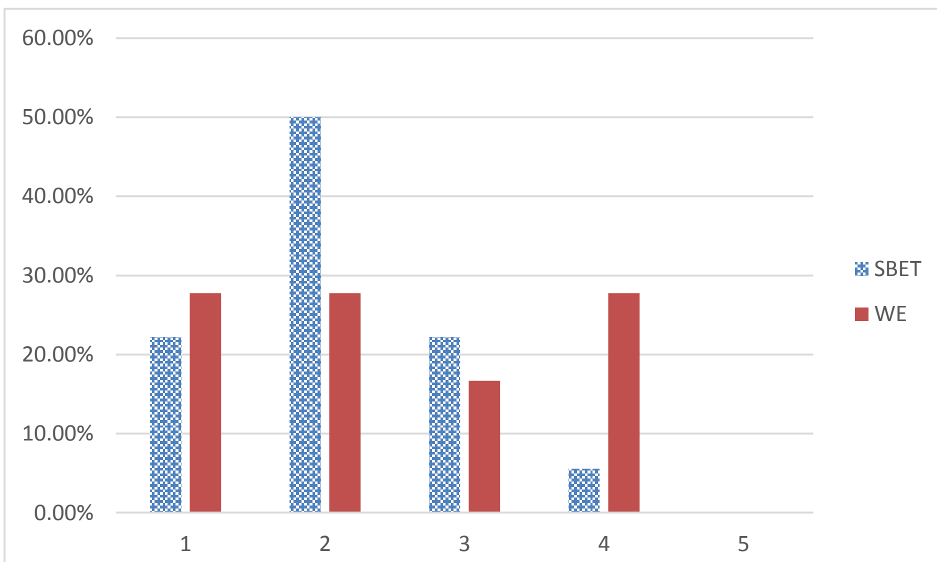


Figure 36: SBET and WE comparison for question 2 (“It was easy to finish the task without any difficulty.” – 1. Strongly Agree, 2. Somewhat Agree, 3. Neutral, 4. Somewhat Disagree, 5. Strongly Disagree).

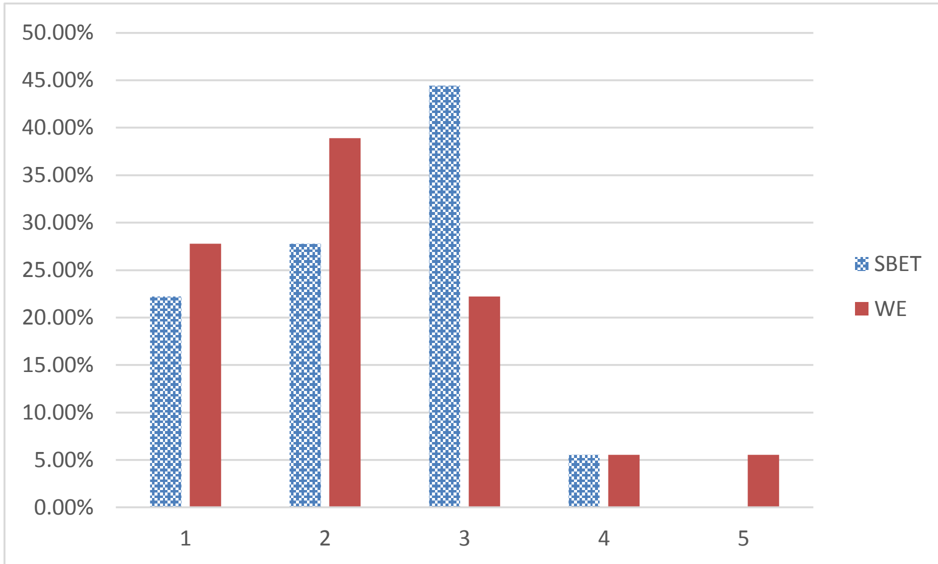


Figure 37: SBET and WE comparison for question 3 (“It was easy to easy to control probe using finger.” – 1. Strongly Agree, 2. Somewhat Agree, 3. Neutral, 4. Somewhat Disagree, 5. Strongly Disagree).

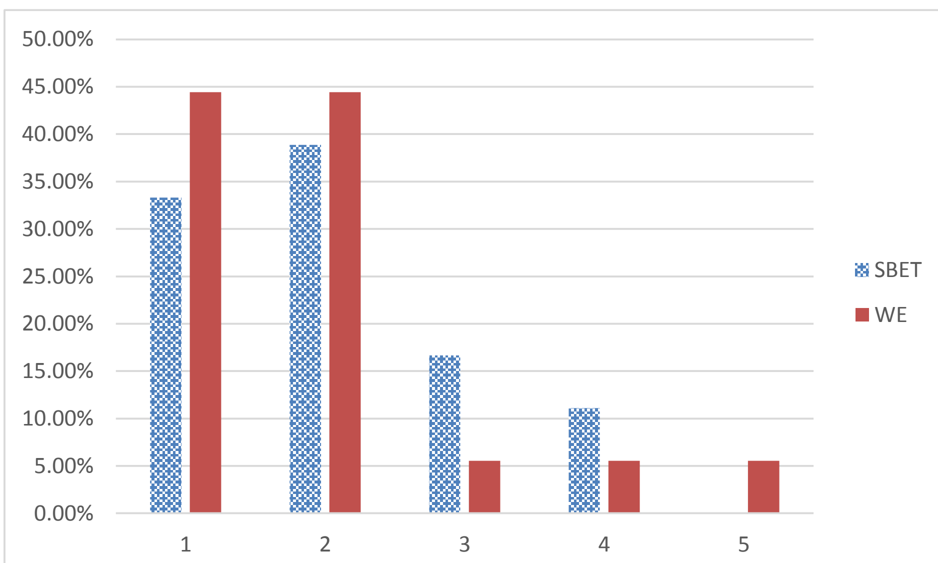


Figure 38: SBET and WE comparison for question 4 (“It was easy to use micro-adjustment function of the application.” – 1. Strongly Agree, 2. Somewhat Agree, 3. Neutral, 4. Somewhat Disagree, 5. Strongly Disagree).

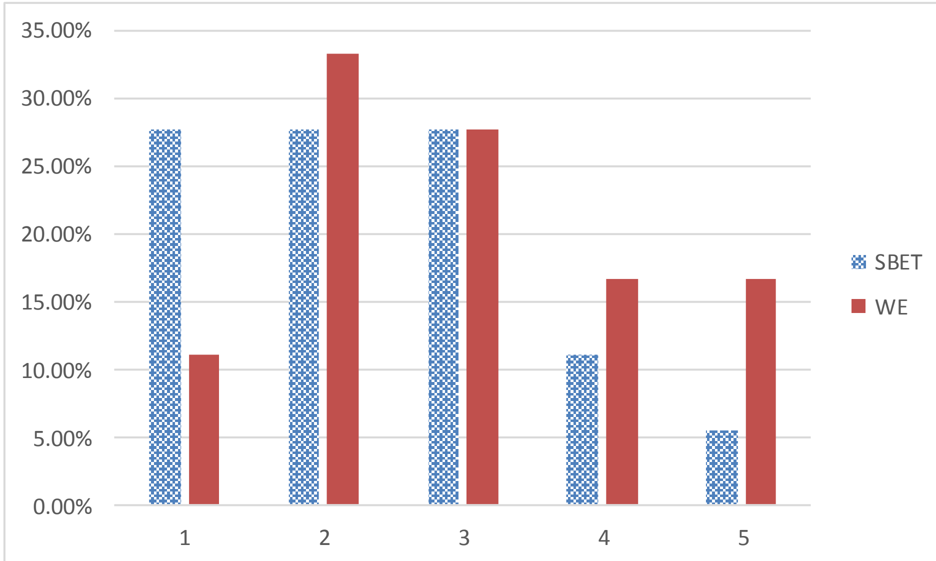


Figure 39: SBET and WE comparison for question 5 (“It was easy to find specific target.” – 1. Strongly Agree, 2. Somewhat Agree, 3. Neutral, 4. Somewhat Disagree, 5. Strongly Disagree).

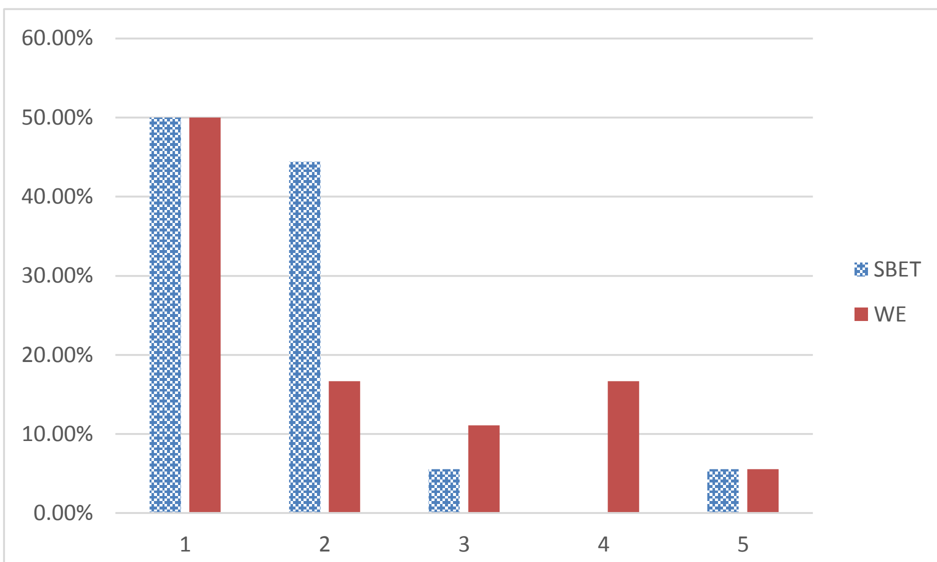


Figure 40: SBET and WE comparison for question 6 (“The system respond well to interactions.” – 1. Strongly Agree, 2. Somewhat Agree, 3. Neutral, 4. Somewhat Disagree, 5. Strongly Disagree).

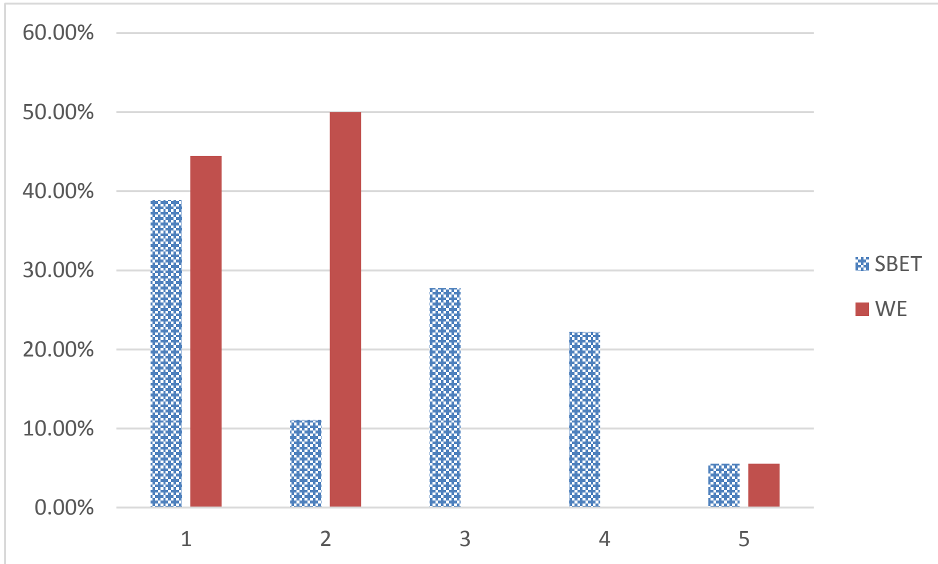


Figure 41: SBET and WE comparison for question 7 ("It is hard to find small targets when components are scattered on the screen" – 1. Strongly Agree, 2. Somewhat Agree, 3. Neutral, 4. Somewhat Disagree, 5. Strongly Disagree).

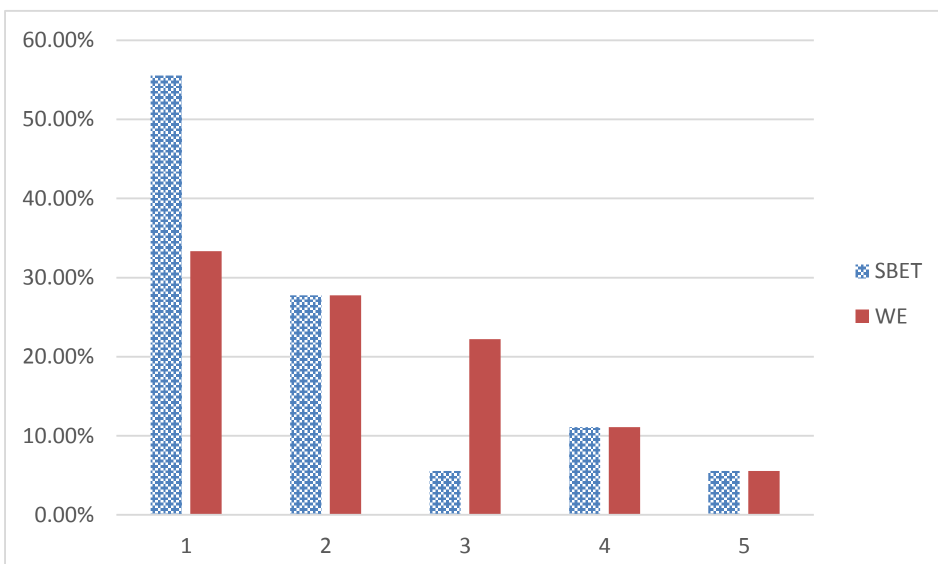


Figure 42: SBET and WE comparison for question 8 ("The application is very useful to find both large and small targets" – 1. Strongly Agree, 2. Somewhat Agree, 3. Neutral, 4. Somewhat Disagree, 5. Strongly Disagree).

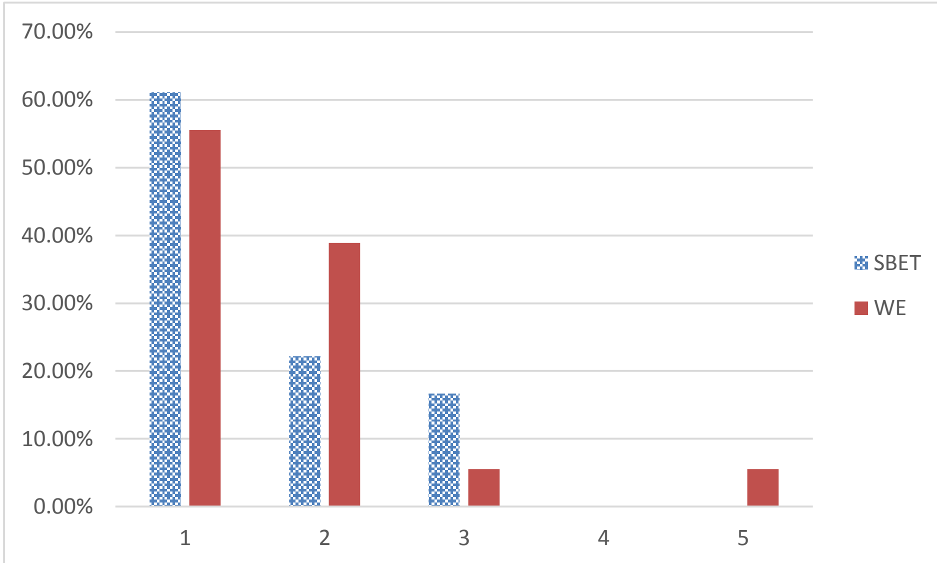


Figure 43: SBET and WE comparison for question 9 ("It is a novel way to interact with 3D model on touch screen" – 1. Strongly Agree, 2. Somewhat Agree, 3. Neutral, 4. Somewhat Disagree, 5. Strongly Disagree).

After running t-tests, the P-values for question 1, 2, 3, 4, 5, 6, 7, 8, 9 (see Figure 35, 36, 37, 38, 39, 40, 41, 42, 43) were: P1 = 0.55, P2 = 0.33, P3 = 0.74, P4 = 0.28, P5 = 0.23, P6 = 0.12, P7 = 0.09, P8 = 0.15 and P9 = 0.8, indicating no significant difference between two different techniques. While no statistically significant results were found, the graphs reveal some interesting patterns. For example, Figure 35 reveals that about 26% of participants using WE thought the interface of application was not easy to use compared to no participants believing that the SBET interface is hard to use. Furthermore, fewer participants (50%) thought that SBET was hard to use for finding small targets (Figure 40), than in the WE condition (94%). Ease of finding and selecting small targets is a key goal for our method. However, WE was rated a little better when it comes to probe control (Figure 37) and micro-adjustment (Figure 38) as compared to SBET. We speculate that participants favored WE for probe control by both finger and button micro-adjustment since our SBET method required more complex interactions. For example, in WE method, participants only need to operate a probe to explore 3D model while in SBET participants need to also manually control the selection of the current layer to create exploded view which requires a certain amount of additional interactions.

4.5.6 Interview

We interviewed each participant at the end of the session and analyzed results based on five key questions.

When asked question “What is your overall impression using this technique?” 85% of participants using SBET said that it was very good compared to 60% of participants using WE. Among these 85% of participants, we presented some of the responses from participants using SBET: Participant 1 said, “SBET is pretty good and also very intuitive”. Participant 11 said, “It is very effective method to select small parts from 3D model as long as the explosion can move a little slower”. Participant 21 said, “It is a fantastic application and it helps visualize 3D model in a novel way”. Some of the responses from participants using WE: Participant 2 said, “It is not very hard for finding little things among a lot of other little things. If it could be done with layer by layer, it would be good option”. Participants 8 said, “It is alright, but it gets very difficult when the target becomes very small”.

We described SBET in detail to participants who performed tasks using WE in the interview and also described WE in detail to participants who performed tasks using SBET as an alternative method and asked “If you are given alternatives for doing this 3D explosion, which one do you think is better?”, 30 out of 36 participants reported that they found that the SBET method was more helpful when it comes to finding small targets which are not visually accessible. They believed that it reduced the level of difficulty and stress in the process when all the components are not scattered on the screen. In addition, they indicated that the level of difficulty did not vary much as the target’s size became smaller and the model became more complex. As Participant 9 who used WE said, “WE is no good, especially when there are a lot of objects spread on the screen”. Participant 8 who used SBET said, “Technique 1 (SBET) is more helpful than Technique 2 (WE), you can narrow down your selection by removing objects layer by layer”. But for the WE method they said that it was very hard to focus on the target when it’s small and there when a lot of components exploded simultaneously. As participant 32 who used SBET said, “There are too much small stuff on the screen and it makes finding target object very hard”.

When asked “What difficulties did you experience with present technique?” some responses of participants using SBET were: Participant 3 said, “I lost track of location to target when going deep to next layer because I found it hard to recognize the model when losing objects layer by layer”. Participant 7 said, “I accidently clicked on a part when I am doing camera rotation”. Participant 15 said, “I need a couple of days to get used to this application if I want to perform all tasks faster”. Participant 19 said, “Sometimes probe made objects moving so fast, but the micro-adjustment helped a lot in the process”. Other responses from participants using WE were: Participant 6 said, “too many similar stuff on the screen and it was very hard to get the right one”. Participant 14 said, “Sometimes the exploding objects moved so fast and everything was exploded in many directions”. According to above statements from participants using two different methods, it seemed that WE group expressed more concerns about visual clutter on a limited screen, while SBET group was worried about losing some context doing layer by layer explosion.

Additionally, some users found that it was confusing when the targets disappeared within the previous layers in the SBET approach and they had to go back to the earlier layers to search for parts. Some other participants thought that WE was somehow faster when locating large targets because its procedure is simple and they only needed to explode once for the 3D model. However, participants complained about the similarity of components that made finding parts hard in WE method. As participant 28 stated: “this method is hard to choose targets looking the same with others and SBET method is much better, especially for a lot of similar and tiny parts”.

4.5.7 Summary

We analyzed and illustrated study results of quantitative data: probe movements, camera rotations, task finishing time, wrong target selection and method preference on questionnaire. Also, we presented interesting findings about interview results. The reason why we analyzed probe movements and camera rotations is that it tells us how participants interact with two different techniques.

Table 10: Summary table of main effects for each of independent variable (N.S. = Not Significant and S. = Significant).

Dependent Variables	Independent Variables		
	Technique	Target Size	Model Complexity
Task finishing time	N/A	N/A	S.
Number of wrong target	S.	S.	N.S.
Number of probe movements	N.S.	S.	S
Number of camera rotations	N.S.	N.S.	S.

Although there were no 2-way or 3-way interaction effects on probe movements and camera rotations, the model complexity turned out to be a main effect as we can see from Table 10. For number of probe movements, target size is also a significant factor affecting the how participants move proves on both two different techniques. Only one Interaction effect of TargetSize X Method was found significant in task finishing time, indicating that SBET performed better when target size was very small. For main effects of task finishing time and wrong target selection, target size seemed to be main effect. Also, model complexity was a significant factor for task finishing time. Moreover, there was significant difference between two techniques on wrong target selection while no significant difference between two techniques showed on task finishing time.

Overall, target size seemed to be most influenced factor for all with-subject and between-subject variables. This also validated some of responses given by participants in the interview process that the small target was very hard to find and select for both techniques.

CHAPTER 5 CONCLUSIONS

In this chapter, we summarize our research method and study results. Then we discuss current limitations and future work.

5.1RESEARCH METHOD SUMMARY

Our initial purpose for conducting this research and the associated user study is to design and assess solutions for mechanics. In particular, we aimed to support efficient in situ search and selection of small and occluded components in 3D models (such as aircraft) with the help of mobile devices. With this goal in mind, we designed and developed a scale-based exploded view technique as a suitable method for performing such tasks on mobile devices. Our design was informed by site visits and ongoing remote discussions with engineers in the Boeing Company. In order to make the system feasible on mobile devices, we reduced the computation complexity of the application as much as possible.

5.2 STUDY RESULTS SUMMARY

By comparing the performance of two distinguishable exploded view techniques that are both feasible for use on mobile devices, we are able to conclude some interesting and useful results. Overall, the average time of finishing the same tasks using SBET were generally less than using WE and also SBET performed significantly better for eliminating the number of wrong targets selected. This could be critical if mechanics tried to perform other operations after selecting specific parts that depended on correct selections. For example, if they wish to see some parameters of a component in a 3D virtual model and after they select the part they incorrectly thought was the target, the application showed parameters, it may take considerable time to realize that they made an error and subsequently reselect again. So, although the timing for the selection of objects was not significantly different within our controlled study, the higher number of errors in the WE method could substantially increase the average task completion time in practice, depending on the ramifications on the additional errors. Therefore, it is vital that users can select a part with minimum mistakes. However, we do not attempt to quantify additional delays as it would be highly dependent on circumstances. SBET has also shown to be adept for finding small targets within a fairly complex model without too much user stress. The smaller the target becomes and the more complex the model is, the better SBET tends to perform when compared to WE.

5.3 LIMITATIONS AND FUTURE WORKS

Although our method showed stronger performance in terms of accuracy comparing with existing whole exploded view approach, we still need to address several problems as discussed below.

5.3.1 Same Position Objects

The algorithm we used for pushing away components and creating exploded view is centered on the 3D position of objects, which means almost every calculation requires position parameters. Therefore, if the 3D position of two or more objects is the same, then objects with the same position will move together as if they were never separated according to the principle of the algorithm. For example, when we look for the target object A and there is object B covering the A with the same position, A and B will move together when we try to use interactive probe to explode the model. In other words, the target A will never reveal itself since the object B always moves with it. In this case, it becomes very difficult to separate A and B which makes finding and selecting the target A problematic. In future work, one might detect the co-location of objects and impose an additional artificial spatial separation.

5.3.2 Similar Objects

From the interview feedback from study participants, we also learned that similar objects make target selection harder since it confuses users when all similar objects explode at the same time. For example, participants first acquire spatial information about the target object from the view section of the application, they can't be certain about the exact position when the target is extremely small. So when the target and surrounding objects explode under the influence of red probe, objects similar to the target that also stay close to the true target may confound the users' judgment of choosing the right target. However, it is worth pointing out that if the object is identical, selecting any one instance of an object may actually be sufficient.

5.3.3 Objects with Similar Colors

Another useful feedback item we received is that objects with the same color complicate the target selection process as well. Since every component of the 3D model is colored in some way, sometimes participants found it difficult to distinguish the target object if two or more objects were colored with a similar color. This issue is more taxing when many objects are rendered with same color, which stay close to the target object. More intelligent assignments of color within local areas may help to mitigate this issue.

5.3.4 Objects in a Dense Environment

As discussed in the user study section 4.5.2, there was an abnormal case (complexity level 2, target size 1, task number 4) in which the timing and error rate showed an unusual pattern comparing to the other cases. The reason behind is this that the target object was in the center of model in which its surrounding environment was dense. The scale-based exploded view method is able to reduce the visual clutter since it tries to separate parts from each other to reveal internal targets. However, when there are so many objects centered on the target and screen size of mobile devices is limited, it is still challenging for users to select the right target. Detecting and handling dense areas separately may further assist the user to deal with this issue.

5.3.5 Model Complexity

Considering the limited CPU and GPU power of mobile devices, we were able to render a 3D model containing up to 450 objects, which was the size of the most complex model in our user test cases. However, within this scope, our study analysis showed that as the model gets more complex, the time and error rate increase accordingly. The aircraft models created by the Boeing Company has millions of parts and so does the corresponding 3D model, so it is impossible to render entire model on mobile devices. However, we note that the full 3D model of a 747 could not even be viewed at once instance on a standard desktop computer either. So, we simply note here that these extremely large models must be separated into smaller sets of related parts. Then we can apply our method on each collection of parts and provide effective methods to search and locate small and occluded targets in the 3D model.

5.3.6 Future Work

Other possible exploded view approaches on low-end devices might be designed to improve the speed or error rate performance. It would also be worth evaluating to what extend the lack of object-to-object blocking has on the final results. In our method, we do not consider blocking or object containing information between components because the computation of this information is too expensive on the mobile devices, and would further reduce the number of object that can be rendered.

Our work is the first study we are aware of that evaluates the use of exploded views specifically on mobile devices and as such we hope that this work can begin a process of further design and evaluation in the area.

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Appendix A Email Recruitment Notice

We are recruiting participants to take part in a research study that evaluates a novel selection method called scale based exploded views for selecting objects within 3D models on an android tablet. We are looking for students, faculty or staff members from Dalhousie University who are fluent in English and have some experience with touch screen devices.

The study will be conducted in a quiet room on the campus of Dalhousie University. Firstly, a researcher will go through an introduction section of the study and ask you to sign a consent form to do the study. Then you will need to fill out a background questionnaire. After that, you will perform several tasks related to the selection of 3D models on an android tablet. Finally, there will be a post-task questionnaire and an interview. Compensation is $15 for participation in the study.

If you are interested in participating, please contact Zezi Ai (zai@cs.dal.ca).

Appendix B Poster Recruitment Notice

Recruitment Notice

Scale Based Exploded Views: Evaluating object selection methods on mobile devices

We are recruiting participants to take part in a research study that evaluates a novel selection method for selecting objects within 3D models on an android tablet. We are looking for students, faculty or staff members from Dalhousie University who are fluent in English and have experience with touch screen devices.

The study will be conducted in a quiet room on campus of Dalhousie University. Firstly, a researcher will go through introduction section of the study and ask you to sign a consent form to do the study. Then you will need to fill out a background questionnaire. After that, you will perform several tasks related to the selection of 3D models on an android tablet. Finally, there will be a post-task questionnaire and an interview. Compensation is $15 for participation in the study.

If you are interested in participating, please contact Zezi Ai (zai@cs.dal.ca).

Appendix C Screen Email

Thank you very much for your reply to the recruitment notice. I have a few questions to ask before you can participate in our study.

1. Do you speak and read English fluently?

2. Do have any experience with touchscreen devices, such as tablets?

3. Do you have any experience of using 3D models such as using AutoCAD, 3DS Max software or playing 3D games?

Please answer each question and return them in an email to me. Again, thank you for showing interest in this study. Contact information is Zezi Ai (zai@cs.dal.ca).

Appendix D Informed Consent

Scale Based Exploded Views: Evaluating object selection methods on mobile devices.

Principal Investigator:

Zezi Ai, MCS Thesis student, Faculty of Computer Science (zai@cs.dal.ca)
Dr. Stephen Brooks, Faculty of Computer Science (sbrooks@cs.dal.ca)
Dr. Kirstie Hawkey, Faculty of Computer Science (hawkey@cs.dal.ca)

Contact Person:
Zezi Ai, MCS Thesis student, Faculty of Computer Science (zai@cs.dal.ca)

We invite you to participate in a research study being conducted by Zezi Ai and Drs. Stephen Brooks and Kirstie Hawkey at Dalhousie University. This study is entirely voluntary and you can withdraw from it anytime you wish. You will receive compensation of $15 for your participation and even if you withdraw in the middle of study, you will still receive compensation. Your academic (or employment) performance evaluation will not be affected in any way by whether or not you take part in the study. If you have any further questions about the study, please contact Zezi Ai.

The study is about evaluating 3D object selection methods on mobile devices and it should take approximately 40 minutes. The researcher will guide you through the beginning with an introduction to the study. You will be given several tasks related to the usability of the application. We will record your voice, times and finger interaction with the tablet during the study after you log in. After that, you will need to fill out a post-task questionnaire and participate in a short interview with the researcher.

You might feel frustrated, bored or fatigued during the study as you will interact with a mobile tablet by holding it in your hand. However, you can always take a break if you feel tired and a researcher will be available during the study if you have any questions.

We will recruit 36 participants for this study and all personal data from the study will be kept strictly confidential. To preserve your identity and anonymity, we will use pseudonyms (e.g., P1, P2) to denote you. All the data will be kept in a secure location under confidentiality in accordance with university policy for 5 years post publication. Also, all the data will be used for research purpose only and there won't be any commercial company collecting this data.

In the event that you have any difficulties with, or wish to voice concerns about, any aspect of your participation in this study, you may contact Catherine Connors, Director, Office of Research Ethics Administration at Dalhousie University's Office of Human Research Ethics for assistance: phone: (902)494-1462, email: Catherine.connors@dal.ca.

"I have read the explanation about this study. I have been given the opportunity to discuss it and my questions have been answered to my satisfaction. I hereby consent to take part in the study. However, I understand that my participation is voluntary and that I am free to withdraw from the study at any time."

Participant	Researcher
Name: ______________________________	Name: ________________________
Signature: ___________________________	Signature: _____________________
Date: ______________________________	Date: _________________________

"I understand and consent that my participation in the experiments will be audio recorded for the purpose of analysis. I understand that this is a condition of participation in the study, and I understand that this audio record will not be used in the publication or presentation of results."

Participant	Researcher
Name: ______________________________	Name: ________________________
Signature: ___________________________	Signature: _____________________
Date: ______________________________	Date: _________________________

“I want to read any direct written quotes prior to their use in reports and I understand that the anonymity of textual data will be preserved by using pseudonyms.”

[If this option is chosen, please include a contact email address: _________________]

Participant	Researcher
Name: ______________________________	Name: ________________________
Signature: ___________________________	Signature: _____________________
Date: ______________________________	Date: _________________________

If you are interested in seeing the results of this study, please check below and provide your email address. We will contact you with publication details that describe the results.

“I would like to be notified by email when results are available via a publication.”

[If this option is chosen, please include a contact email address: _________________]

Participant	Researcher
Name: ______________________________	Name: ________________________
Signature: ___________________________	Signature: _____________________
Date: ______________________________	Date: _________________________

Appendix E Background Questionnaire

1. Gender: ☐ Male ☐ Female

2. Age:

3. Participant ID:

4. How familiar are you with mobile devices (tablet or phone)?

☐ Very familiar ☐ Somewhat familiar ☐ Not familiar

5. How familiar are you with touchscreen?

☐ Very familiar ☐ Somewhat familiar ☐ Not familiar

6. How familiar are you with 3D models?

☐ Very familiar ☐ Somewhat familiar ☐ Not familiar

7. Have you ever interacted with 3D models on a computer?

☐ A lot ☐ Sometimes ☐ Not at all

8. Do you have experience on interacting with 3D models on a tablet or other mobile devices?

☐ A lot ☐ Some ☐ A little ☐ None

Appendix F Post-task Questionnaire

Please respond to the following statements using the given scale (circle response):

1.	The interface of application is easy to understand.	**1** Strongly Disagree	**2** Somewhat Disagree	**3** Neutral	**4** Somewhat Agree	**5** Strongly Agree
2.	It was easy to finish the task without any difficulty.	**1** Strongly Disagree	**2** Somewhat Disagree	**3** Neutral	**4** Somewhat Agree	**5** Strongly Agree
3.	It was easy to control the probe using accelerometer on z axis.	**1** Strongly Disagree	**2** Somewhat Disagree	**3** Neutral	**4** Somewhat Agree	**5** Strongly Agree
4.	It was easy to use finger to show the position of probe.	**1** Strongly Disagree	**2** Somewhat Disagree	**3** Neutral	**4** Somewhat Agree	**5** Strongly Agree
5.	It was easy for me to find the targeted objects.	**1** Strongly Disagree	**2** Somewhat Disagree	**3** Neutral	**4** Somewhat Agree	**5** Strongly Agree
6.	The responds given by application are appropriate and accurate.	**1** Strongly Disagree	**2** Somewhat Disagree	**3** Neutral	**4** Somewhat Agree	**5** Strongly Agree
7.	I lost the probe when I move it behind the objects.	**1** Strongly Disagree	**2** Somewhat Disagree	**3** Neutral	**4** Somewhat Agree	**5** Strongly Agree
8.	I can't select the targeted objects because it is still too small for me.	**1** Strongly Disagree	**2** Somewhat Disagree	**3** Neutral	**4** Somewhat Agree	**5** Strongly Agree
9.	I think it is a novel way to interact with 3D models.	**1** Strongly Disagree	**2** Somewhat Disagree	**3** Neutral	**4** Somewhat Agree	**5** Strongly Agree

Appendix G Interview Questions

(1) Did you find the task easy? Why?

(2) What difficulties did you have with the technique you just used?

(3) What improvements can this technique benefit from in the future?

(4) Do you think it is easy to use the probe to interact with the 3D models? Why?

(5) What is overall impression using this technique?

Appendix H Participant Payment Receipt

My signature below confirms that I received an amount of 15 CAD from Zezi Ai as an honorarium payment for participating in the "Scale Based Exploded Views: Evaluating object selection methods on mobile devices" research project.

I understand this honorarium is taxable income and it is my responsibility to claim it on my income tax as Dalhousie University will not be issuing a T4A for this payment.

Name (please print): ________________________________

Signature: ________________________________

Date: ________________________________

Appendix I 3D Models for the User Study

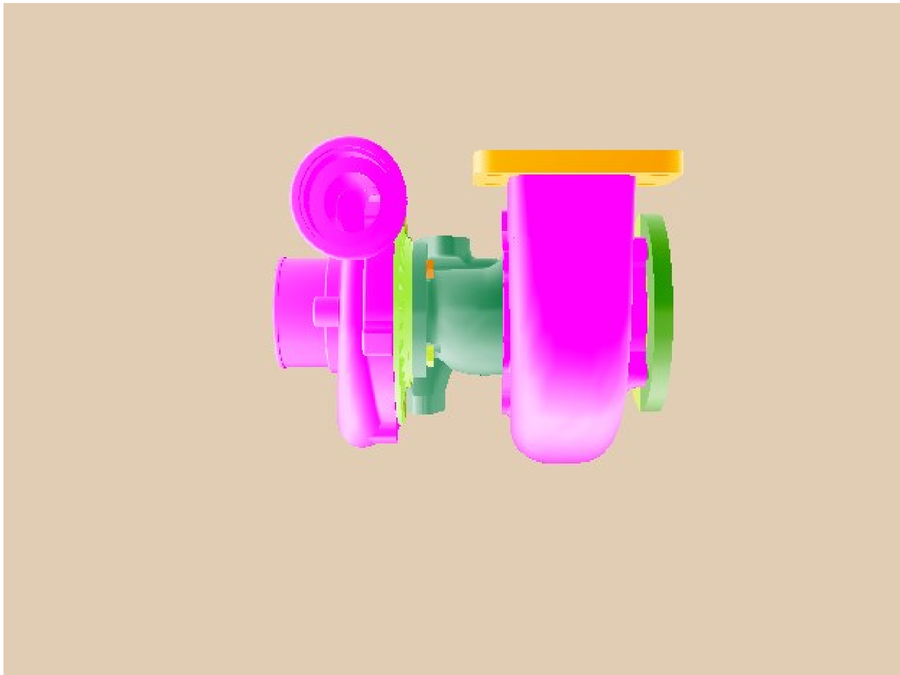

Figure 44: Case model with complexity level 1.

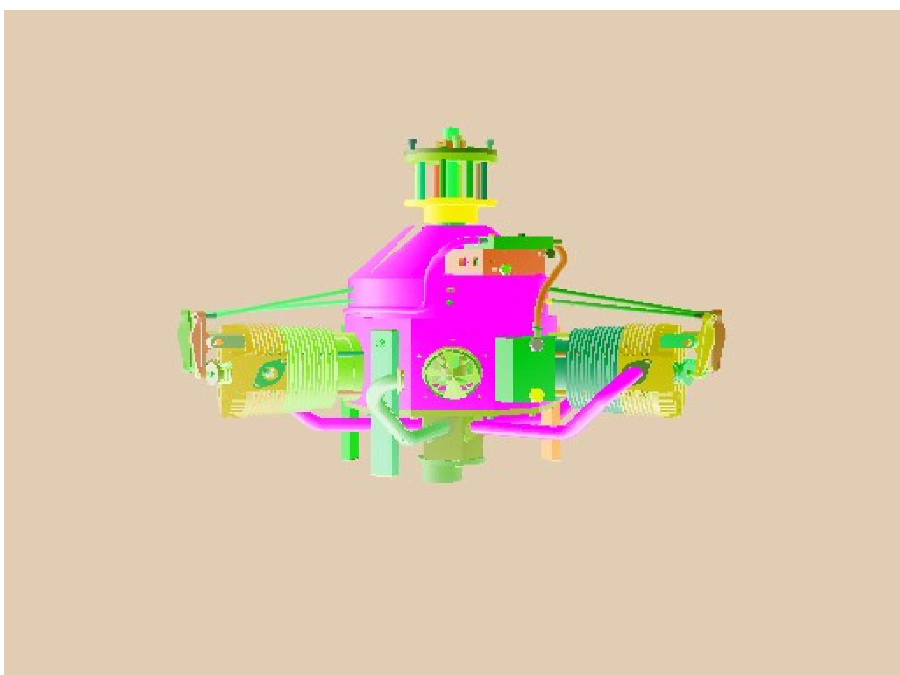

Figure 45: Case model with complexity level 2.

Figure 46: Case model with complexity level 3.

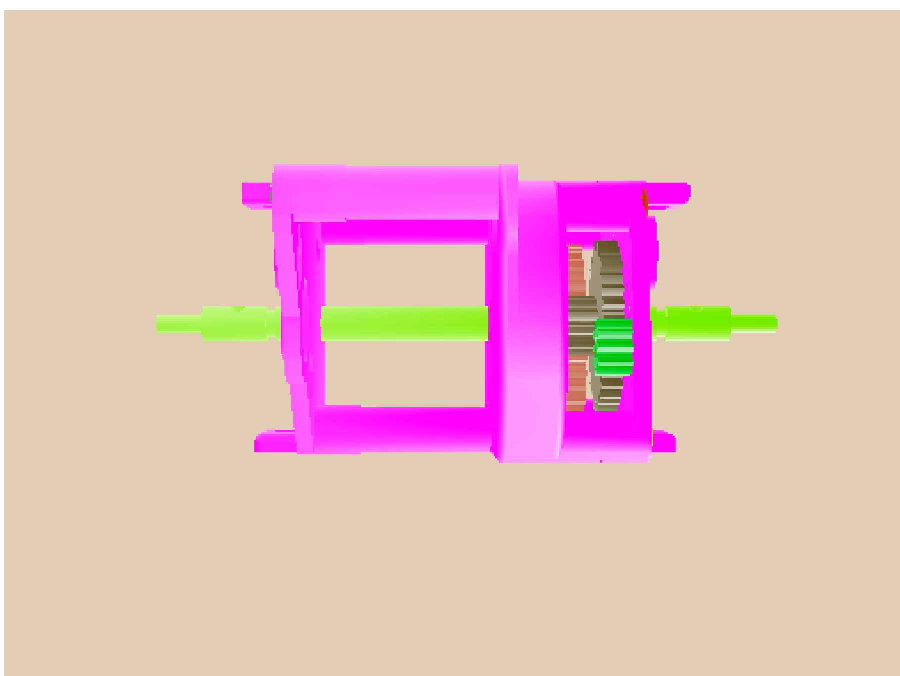

Figure 47: Training model.

Appendix J Tasks for the User Study

Figure 48: Task 1 (model complexity = 1 & target size = 1).

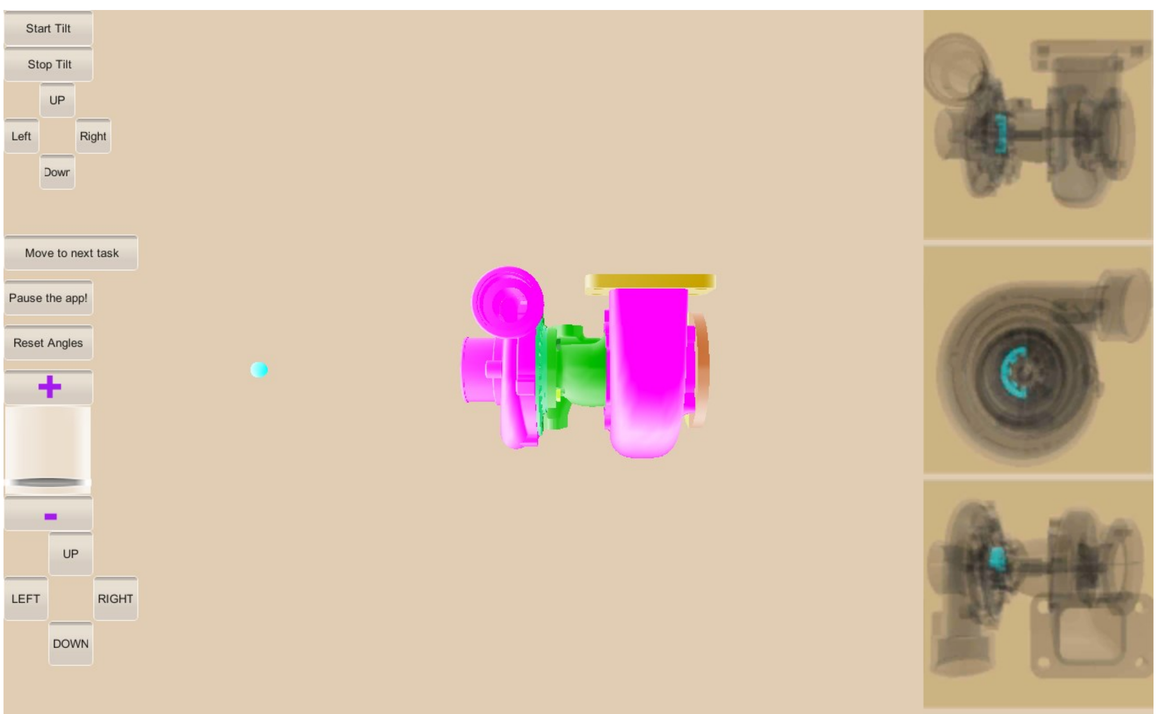

Figure 49: Task 2 (model complexity = 1 & target size = 2).

Figure 50: Task 3 (model complexity = 1 &. target size = 3).

Figure 51: Task 4 (model complexity = 2 & target size = 1).

Figure 52: Task 5 (model complexity = 2 & target size = 2).

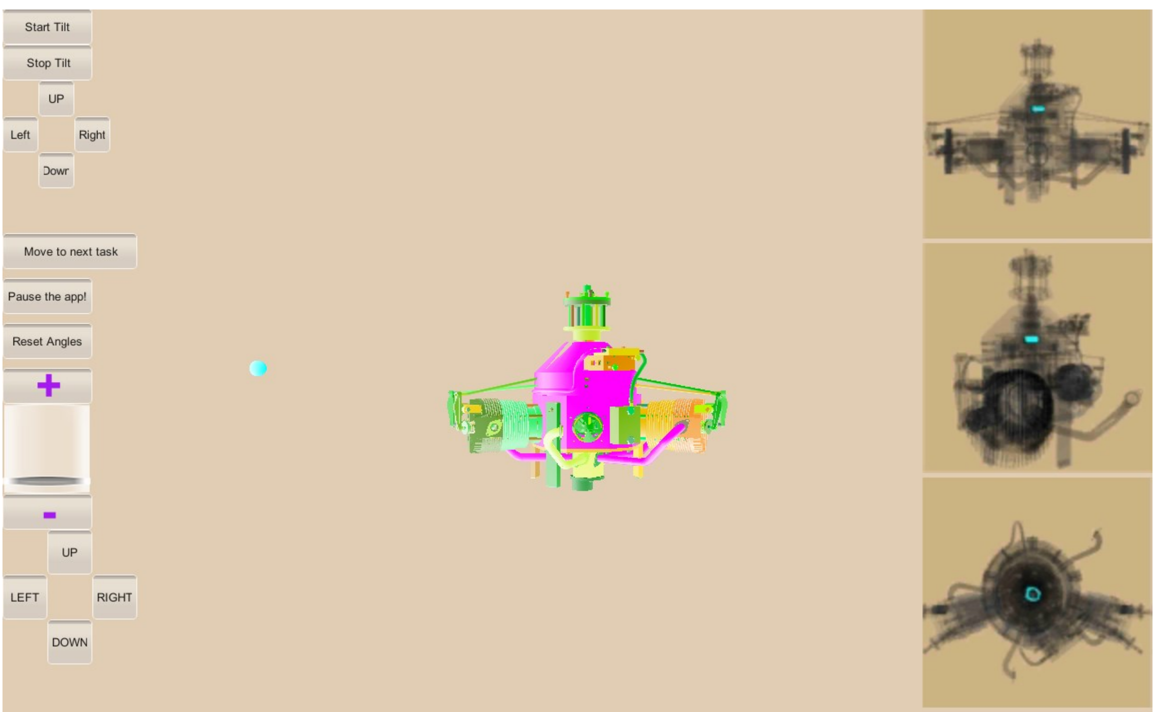

Figure 53: Task 6 (model complexity = 2 & target size = 3).

Figure 54: Task 7 (model complexity = 3 & target size = 1).

Figure 55: Task 8 (model complexity = 3 & target size = 2).

Figure 56: Task 9 (model complexity = 3 & target size = 3).