

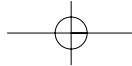
GENERAL CONCLUSION ON THE VALUE OF TWO-HANDED 3D INTERACTION FOR CONCEPTUAL MODELING

CHAPTER

This chapter presents the conclusions of this work. The unifying hypothesis was that computer support of conceptual modeling would benefit from two-handed operation in 3D. In the introduction, the reasoning behind the hypothesis is summarized. Then the conclusions from two evaluations are presented. These will show that two-handed 3D interaction does have advantages for conceptual modeling. In the first evaluation, one-handed operation was compared to two-handed operation. It was found that two-handed operation is faster and that it leads to a division of workload between the two hands without increasing the total workload. In the second evaluation, several two-handed interfaces were compared. This evaluation identified improvements to the interface to make it more comfortable to operate and more generally applicable. It was found that the improvements did not degrade performance while maintaining the same workload. The evaluations were carried out with a new CAD system that was built from the ground up because available CAD systems could not be used. In developing and prototyping the ID8Model system, several lessons were learned regarding interaction devices and software. The chapter ends with pointers for future research. During the research, several issues were encountered that were set-aside for later development. These are summarized and followed by proposals for modifications to the system that can further increase its appropriateness for conceptual modeling.

6.1 Introduction

Previous studies of designers at work and shortcomings of the interaction with current CAD systems motivated the investigation of the potential of 3D interaction and two-handed operation for computer supported conceptual modeling. Using 3D interaction devices, movements of the designer's hand in 3D can be captured. Therefore, the speed of accomplishing modeling tasks can improve

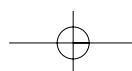


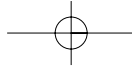
because the designer does not have to divide the intended actions into successive 2D movements with the mouse. Besides improved speed, 3D interaction can result in a more direct way of interacting with the system and with the model being created. Because of the more direct interaction, the control over the modeling tasks can be expected to grow. However, the fact that most CAD applications are created for use in combination with 2D interaction devices means that the interaction techniques may have to be redesigned for use with 3D interaction devices. In fact, it was encountered that most CAD applications will need to be rewritten entirely in order to take full advantage of bimanual 3D interaction. Therefore, an integrated approach is needed considering both interaction devices and interaction techniques.

Two-handed operation of CAD tools is not common. In fact, two-handed operation of any computer system is seldom encountered despite the fact that the benefits of two-handed operation have been established in previous research, as outlined in Chapter 2. The explorative phase of the research showed that there is more involved in realizing effective two-handed operation than the addition of an interaction device to the system. That was confirmed by literature on the subject and it was found that for effective two-handed operation, it has to be realized that the hands have different roles in bimanual activities.

6.2 Observed advantages of two-handed interaction

The first evaluation of two-handed operation consisted of a comparison of one- and two-handed operation with an assembly task in 3D. An assembly task was chosen because it represents a common task in conceptual modeling. It is more involving than the tasks commonly used in research on interaction devices such as target acquisition, docking and matching tasks. Performance was the first variable established in the evaluation and measured with the time needed to complete the assembly. The other variable, workload, was measured by establishing two variables. The distance variable represents the amount of distance that the hands moved in completing the assembly. The rotation variable represents the amount of rotation with hand during the assembly. The accuracy of an assembly was regarded of minor importance compared to performance and workload because accuracy is not the main concern





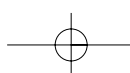
of a designer in conceptual modeling activities. Therefore, accuracy was implicitly present only because a fixed accuracy was used for a successful placement of pieces.

In the evaluation, 3D interaction devices were not compared to the standard operation of CAD systems directly. The main reason was that previous research had already established that 3D interaction devices could be successfully used for controlling 3D positioning and orientation tasks (Zhai, Buxton & Milgram, 1996; Hinckley, Tullio, Pausch, Proffitt, & Kassell, 1997). Benefits of two-handed operation had been established before also but not for two-handed operation of 3D modeling tasks. The observations of the one-handed use of a 3D interaction device confirmed the suitability of 3D interaction devices and suggested that working with those devices is easy to learn and faster than working with the mouse.

The important findings of the first evaluation relate to two-handed operation. By comparing the completion times of one- and two-handed operation in an assembly task, we found that working with two hands is faster than working with one hand. The ratio of two- and one-handed completion times was 0.71¹. This result was found after approximately an hour of practice by subjects who were not experienced in operating the computer with two hands. This short period suggests that two-handed 3D interaction was easy to learn, especially since it was expected that subjects were required to learn a lot of skill in a short time.

Next to completion times, the workloads of one- and two-handed operation were compared. It was found that the workloads of one- and two-handed operation did not differ significantly. In terms of distance this means that the distance moved with a single interaction device while working with one hand did not differ from the distance moved with both devices in the two-handed situation. This was surprising because it was anticipated that working with two devices would increase the total distance needed to complete the task. The same effect was found for the rotation of the hands. Two-handed operation led to the same total rotation of both hands as single-handed operation did for the rotation of one hand only. The invariance of total translation and rotation in itself was a striking finding.

¹ The ratio of 0.71 is the ratio of mean completion times. These means were established with a standard deviation of SD = 0.22.



Instead of increasing the total workload, two-handed operation was found to lead to a division of workload between the hands. The experimental results showed that this occurred in the assembly task. More than a third of the total distance was traveled with the non-dominant² hand and the workload of the dominant hand reduced with the same amount. For rotation, an even larger amount of transfer was observed. The non-dominant hand was used for more than half of the total rotation of both hands.

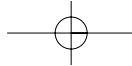
6.3 Choosing between two-handed 3D interaction techniques

In the second evaluation, two aspects of two-handed interaction techniques were compared on performance and workload. The first aspect was the clutch mechanism of the system and the second was the selection mechanism. Evaluating the clutch mechanism was in part motivated by the observations of subjects working with the system used in the previous evaluation. It was sometimes observed that users had difficulties with the clutch mechanism of the system. The clutch mechanism provides users with the possibility to interrupt the coupling between the interaction devices and the controlled objects. The main reason for the presence of a clutch mechanism is to allow a user to remain in a comfortable posture while working with the system. This avoids that users are forced to work with their hands in the air, which can be fatiguing. The operation of the clutch mechanism is analogous to working with the mouse. If a user is working with a mouse in an uncomfortable posture or if the user is running out of desk space, the mouse can be lifted and then lowered at a position more comfortable for the user.

The comfort of a clutch system can outweigh perceptual matches, such as the unification of the display and manipulation spaces. Without a clutch mechanism, the relationship between the position of a hand and its associated cursor is fixed. This provides the user kinesthetic cues about the relation between the real world and the virtual world. For instance, if a user has placed a virtual object at a certain position, it can be retrieved later by moving the interaction device to the same position. In addition, when working with two hands, the relationship of the positions of the hands and the cursors is constant. This provides the user extra kinesthetic cues:

² For a right-hander the dominant hand is the right hand and the non-dominant hand is the left hand, for a left-hander the roles are reversed.

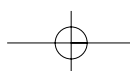
See Chapter 2, page 75 for comments upon this issue.



in this case the ability to know where the hands are relative to each other. Clutching can interfere with both kinesthetic cues and recent research has shown that this may impact performance in conditions with reduced visual feedback (Balakrishan & Hinckley, 1999). With separate clutching, this is indeed the case since a separate clutch mechanism is available for both hands. However, with combined clutching, a user can still use the ability to know where the hands are relative to each other because clutching is activated for both hands at the same time.

The selection mechanism was the other aspect evaluated. The selection mechanism used in the previous evaluation was considered too specialized for the assembly task. It was named dependent selection. Independent selection is more generally applicable and it was compared to dependent selection. The dependent and independent selection techniques differ in the way objects are selected. With dependent selection, a user operates only one cursor with the dominant hand. The cursor is used to identify objects for subsequent movement. The objects controlled with the non-dominant hand are determined by the current selection of the dominant hand. With independent selection, the user operates two cursors, one for each hand. This symmetric approach is perhaps the more obvious approach but the fact that objects need to be selected with both hands was expected to be of negative influence to performance. However, this selection mechanism gives a user the most freedom to decide which objects are under control of which hand. In addition, when objects can be selected with the non-dominant hand, the other hand is free for other activity than selection. This is useful in different tasks than the assembly task, such as shape modification.

With regard to the clutch mechanism, it was found that there was no influence on performance. Preliminary testing had already shown that the percentage of clutch time was low. The experimental results for performance confirmed that the degree of kinesthetic feedback did not influence performance time significantly. This result was found also in the above-mentioned research by Balakrishan and Hinckley (1999). They found that the absolute coupling between the hands (the conditions without clutch or with combined clutch in our research) does not lead to higher performance. That result was found under the condition that the user received continuous visual



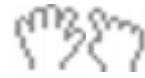
feedback about the positions of the controlled objects. When the amount of visual feedback was reduced, performance reduced.

The experimental results showed that the clutch mechanism does have influence on the workload. Without clutch or with a combined clutch mechanism, users needed to move each of their hands more than with a separate clutch mechanism. In addition, the amount of concurrent activity of the hands was higher with the separate clutch. The most likely reason for both results was observed when users were working with the system. Without clutch or with a combined clutch mechanism, the devices will get in each other's way when objects are brought together for assembly. This forces the user to release one of the objects, to move the device out of the way and then finish the assembly with one hand. The result is that workload increases and concurrent activity reduces.

The results of the surveys showed that the reported fatigue was low for all clutch mechanisms and that there was no clear user preference for a clutch mechanism. This was surprising because it was anticipated that the absence of a clutch mechanism would lead to fatigue. It can therefore be argued that the clutch mechanism is superfluous. Still, a clutch mechanism seems inevitable for a system with spatial interaction. First, subjects in the experiment used the system for short successive periods. In a real design task, users are expected to work with the system for longer periods and therefore, fatigue will probably become a more important factor. Second, device collisions observed in the situation without clutch can be avoided by offering the users a means to displace their hands while working with objects in close proximity to each other.

³ The interface of the condition with independent selection was almost identical to the interface used in the comparison of one- and two-handed operation. It would be interesting to compare the results of those experiments with the results of the experiment described in this chapter. However, the conditions of the experiments were not the same. For example, different profiles were used for selecting subjects and the length of the experiments was different. Hence, the decision to abandon such an analysis.

The experimental results showed that the selection technique had no significant influence on the levels of performance realized. It can therefore be concluded that the results of the previous evaluation hold true for both the dependent and the independent selection technique³. This supports the choice for the more generally applicable independent selection technique. It was surprising that the subjects involved in the experiment did not indicate a clear preference when asked for their favorite selection technique. However, it is expected user preferences will favor independent selection for design tasks since this offers them the most freedom in deciding which objects to manipulate.



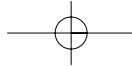
6.4 Development of interaction devices and software

A significant amount of work has been put into the development of interaction devices and the software that employed the devices to operate modeling tasks. The concurrent development of the devices and the software allowed for a close coupling between the two.

Most interaction designers accept the given input devices without reconsidering whether the devices are suited for the task. A chain is only as strong as its weakest link and therefore, it is surprising that current research and development of CAD systems concentrates on the software only. The common approach is to design for the least common denominator of the characteristics of all the devices that can be used with the system. Optimally, an approach should be taken in which the characteristics of the different devices are taken into account. For instance, most computer systems can support both a mouse and a drawing tablet. Next to the position of the pen, tablets can register the tilt and pressure applied on the pen. Most applications however, ignore tilt and pressure values and they use only the position of the pen to mimic the mouse. Using the tilt and pressure as integral part of the interaction rather than as optional add-ons may lead to departures from (and improvements over) current 2D mouse based interfaces.

Two interaction devices were developed with different design philosophies. The Turntable is the more specialized of the two and it was designed for use with the non-dominant hand. Three successive versions that were built gradually evolved into a device for full orientation control of computerized 3D objects. The Turntable was not intended for use as a pointing device. In that sense, it is a specialized device since it cannot be used to identify and position objects. It was intended for use in combination with a range of other devices; each device specialized for a subset of the total functionality of the CAD system.

The Frog device was not designed for the specific use with either hand but instead primarily designed for 3D interaction with both hands. The sensing technology registering the position and orientation of the Frog is commercially available so that the contribution of this research comprises the design of the shape of the device. The main design considerations were that the form of the Frog should afford a precision grip and that the device should offer two buttons. The precision grip offers the user control over

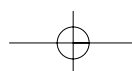


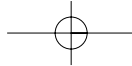
precision tasks, especially since it was expected that the devices needed to be held up most of the time. The buttons can be used to identify objects and to operate the clutch mechanism.

The ID8Model program was created to evaluate 3D interaction and two-handed operation. The program can be used to support a number of different interaction devices. Instead of taking the least common denominator approach, the program takes advantage of the characteristics of each of the devices connected to the system. For example, the mouse can be used to move objects but the movements of the object are restricted to a plane. When the pen of a drawing tablet is used, objects can be moved and the tilt values of the pen are used to control the orientation of the object. In addition, ID8Model allows a user to assign interaction devices to specific tasks or to assign them to either left- or right-handed tool operation. An example of a specific task in the program is the control over the view on the model. A device can be reserved to operate only this functionality. Alternatively, using devices for tool operation allows the user to operate different tools with the same device. All the tools in the program are aware of the hand that is used to hold the device. The paint tool for instance, uses input from the non-dominant hand devices for controlling the position and orientation of the object being painted. Input from the dominant hand is used for painting on the object.

6.5 Conclusion

The aim of the research was to identify and evaluate improvements to computer systems for modeling during the conceptual phase of the design. The literature study reported in Chapter 2 indicated the potential of 3D interaction and two-handed operation as a means to provide the designer with a fast and responsive system for conceptual modeling. The speed of operation was hoped to help the designer concentrate on the design task instead of the operation of the system. In addition, supporting the use of both hands and 3D movements was expected to offer a closer fit of the motor skills of the designer to the modeling actions needed to be operated. This was hoped to reduce the barrier between the designer and the design, resulting in a more transparent interface. After prototyping and building a system for the evaluation, it was found that working with two hands in 3D can indeed be fast and effective. In addition,





the evaluations showed that both 3D interaction and two-handed operation can be learned quickly and are easy to work with.

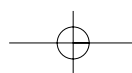
It was learned that designing interfaces employing both two-handed operation and 3D interaction is not self-evident. Effort needs to be invested to ensure the potential benefits materialize. Interaction designers and programmers are easily tempted to make interfaces that allow a user to control a lot of functionality at the same time. The expectation is that performance increases and interfaces will become more useable. The pitfall is that the resulting interface is so difficult to operate that the user is again forced to concentrate on operating the system, rendering the motivation for applying two-handed operation and 3D interaction useless.

It was concluded from a study on two-handed computer human interaction that it is important to recognize the asymmetry of the hands in the interaction design. This notion is still supported but the results of this research suggest that the interaction designer does not necessarily need to make the interface asymmetric. The asymmetry does not have to be located in the interface as long as the users can use their hands in accordance with the asymmetry of normal use. The dependent selection technique was designed for asymmetric use and therefore expected to be superior to the independent selection technique. The results of the evaluation suggested that this was not true. The reasoning is that although the independent selection interface provides the same functionality for both hands, it can still be used to accomplish a compound two-handed task in an asymmetrical way. In assembly for instance, users typically hold one object with their non-dominant hand to facilitate the placement of another object with their dominant hand. Both the interfaces with dependent selection and independent selection provide this mode of operation. The difference is that the independent selection interface allows the user to choose the task solution strategy while the dependent selection interface has the strategy built in.

6.6 Pointers for future research directions

6.6.1 From assembly to shape modification

Although the assembly task used in the evaluations represents a common design task, it forms only part of the functionality needed

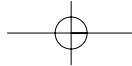


for a complete conceptual modeling environment. It is expected that the results of the evaluations of two-handed assembly can be used in other design tasks to be supported. The first step was already set in the second evaluation where different two-handed interaction techniques were compared. One of the interaction techniques used is considered practical for shape modification tasks where one hand is used to hold or stabilize an object while the other is manipulating the object. This was supported by the experience with interface techniques for several modeling tasks prototyped in the ID8Model environment. The sculpt tool (Figure 3-31 and Figure 3-32) for instance, allows a designer to hold an object with one hand while the other hand changes applies surface displacements by pushing a ball into the surface. The fact that the ball can be moved from outside the surface inwards or from the inside outwards, is an example of functionality that can be offered easily with a computer system.

While the interaction technique of the assembly tool is expected to be adaptable to shape modification, the question of what additional modeling tools the designer needs in conceptual modeling remains unanswered. This question is difficult to answer. An investigation of the use of traditional (physical) modeling techniques might provide an insight as to the functionality the designer needs. However, designers use a variety of materials and tools and not all designers use the same tools. In addition, the fact that designers use certain tools is not proof of that they are optimal tools. Rather, designers have grown accustomed to the tools and therefore, they allow the designer to create models with the desired expression. It seems therefore that the development of improved computer aided modeling tools is a design problem in itself. The skill and creativity of the interaction designer decides whether good tools are found for the support of the industrial designer. In this project, it was learned that studying the use of traditional modeling tools can help the interaction designer in creating CAD tools. Not by offering an overview of the functionality to implement but by indicating the kind of interaction needed to make the tools useful in conceptual design.

6.6.2 Open questions

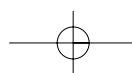
In the research, several issues were encountered that were set-aside for later study. The first issue relates to the nature of two-handed

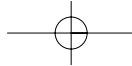


operation. For instance, an assembly task was used in both evaluations of two-handed operation. The task was chosen to represent a high-level design task in which several aspects of two-handed operation were combined. Because of this, the task could not be used to study those aspects in detail and to evaluate their contribution to the total. This was encountered with the stacking task that was evaluated for the comparison of one- and two-handed operation. It was hypothesized that the absence of a performance benefit for two-handed operation was related to the simplicity of the task. However, this could not be verified. The question was raised whether the speed of an assembly of two objects would be faster with two hands than with one hand alone. To be more precise, is there a difference in moving one object to the other with one hand or in moving them to each other with two hands? In the stacking task, many other factors were present that could influence the speed of the assembly. To address the question, a new experiment should be conducted with a task that isolates this effect. Then, it can be established what the contribution of this effect is in the total performance benefit that two-handed operation has over single-handed operation.

Another issue left open was the influence of the display in the system. The emphasis was on the study of the interaction devices and the interaction techniques as a means to improve the interface between the designer and the computer system. The evaluation of the system suggested that with the perspective display on the computer screen, it is sometimes difficult to interpret the state of the design although the user was manipulating with two hands in 3D. Two-handed interaction does contribute in understanding the spatial relations of the design (Hinkley & Pausch, 1997) but apparently, additional help is desirable. Three-dimensional display techniques can be used for that purpose and it would be insightful to establish how much they will contribute to spatial perception and thus to enhanced interaction. The same evaluation could be made for haptic feedback. Will the designer be able to explore the design space better if the possibility is offered to "touch" the design, and to what degree?

In the evaluation of two-handed operation, the accent was on unconstrained movement and speed was preferred over accuracy. The reason is that in the conceptual design phase, designers focus



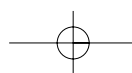


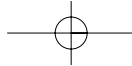
on a quick exploration of the design space and not on the precise formulation of the geometric model. However, there are situations where unconstrained movement is not desirable and where limiting the degrees of freedom is preferred. For example, when positioning an object it can be very helpful when the object is restricted to move along a line, or when evaluating an object, the object could be restricted to rotate about its center without moving. Two approaches for constrained operation can be identified. First, with hardware constraints, the constrained operation is built into the device itself. The Turntable for instance, can only be rotated and it realizes constrained operation by controlling the orientation of an object only. The other constrained operation technique is the use of software. The Frog for instance, can be used for rotation only when the measurements of the Frog's position are ignored.

Both methods have their advantages and disadvantages but it is not clear when to use hardware constraints and when software constraints. With hardware constraints, a clear interface can be created because the shape of a device can express its intended use and it can be optimized for the task it controls. Because of this specialization however, multiple devices are needed to control a modeling application. This has the disadvantage that the devices can clutter the work area and that they need to be acquired before they can be used. Using software constraints has the advantage that just a single device is needed for operating all the functionality in the application. This is also its main disadvantage. The single device cannot be optimized for all tasks it is intended to operate. In addition, using a device with degrees of freedom restricted in software is different than using a device with physically restricted degrees of freedom. For example, when using a slider to control linear motion, the slider can only be moved in the one direction that is controlled. When using a mouse for the same linear task, the mouse can be moved in directions not corresponding to the controlled direction.

6.6.3 Possible system improvements

Devices The design of the Turntable has already iterated through a number of revisions and a number of improvements have been made since the first version. Although the main body of the research was carried out with the Frogs devices, the Turntable is still considered a good device for orienting objects with the non-dominant hand. To



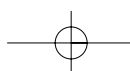


increase the value of the device, it could adhere more closely to the analogy it was thought to realize at the start. Originally, the Turntable was designed to resemble the operation of a potter's wheel with a one-to-one relation between the orientation of the Turntable and that of the controlled object. However, with the current sensing technology mismatches between the orientation of the device and the controlled object can occur. The mouse mechanism inside does not measure the orientation of the Turntable but only changes in orientation. To prevent mismatches, another mechanism should be built that establishes absolute rotation angles.

Although the general response to the Frogs is positive, some aspects of the Frogs can be improved. A complaint of the subjects in the experiments was that the wire hindered them in moving the device. The problem is that the presence of the wire is inevitable with the sensing technology currently used. For the moment, the hindrance could be reduced by upholding the wire so that not all the weight of the wire has to be supported. In the future, there may be a wireless solution possible, or if this is too far fetched, another version of the Frog could lead the wire over the hand and/or arm of the user.

The shape of the Frogs was thought to afford the way in which it should be held. A precision grip, with the Frog held between the fingers and thumb (Figure 4-21), was expected to be most appropriate for the intended use of the Frog. However, some users preferred a power grip, with the Frog held in the whole hand (Figure 4-22), especially for the non-dominant hand. The Frog can be used with both a precision and a power grip but the position of the buttons is not optimal for the power grip. A solution is to duplicate the buttons to facilitate button operation for both grips. Alternatively, if the clutch button could be removed from the Frog, the whole surface of the Frog could function as a selection button by making the surface touch sensitive. With a touch sensitive surface, a user can select objects by squeezing the Frog.

Software The clutch mechanism has been shown to lead to confusion occasionally. Eventually, users will learn how to operate it, but the learning time can be reduced if a way is found to simplify or clarify the operation. The proposed simplification is to do away with the separate clutch modes for each device. Instead, a single clutch



mode for all the devices on the system seems to be clearer while maintaining the same level of operation. With a single and whole-system clutch mode, a separation of the hands can still be supported. A single button can be used that does not have to be located on the device (a footswitch has been shown to work on other systems). The link with the discussion on the shape of the Frogs is clear because the removal of the clutch button from the Frog may help to support alternative grips. The proposed clarification is to give users feed-forward of the outcome of a clutch action. Currently, nothing happens when the clutch button of a device is activated. Therefore, the user has to imagine where to move the devices before releasing the button. Feed-forward could explain where to move the devices to establish a desired manipulation space. Some ideas for feed-forward in the clutch action have already been prototyped with promising results.

The use of alternative interaction devices and two-handed operation forces a reconsideration of the interaction techniques used to interact with the model. The standard interaction techniques cannot be used because these are designed for use with a mouse and keyboard. The problem is that the interaction techniques are closely tied to the underlying geometric models and the software algorithms that act on these models. Until now, the approach has been to use standard geometric models and to create the software for manipulation of the models from scratch. This felt like reinventing the wheel and took much time that was rather spent on studying and improving the interaction techniques. For a continuation of the research, it seems necessary to look for a source of geometric algorithms that can be tapped. Even more since it is expected that the focus in the follow-up research will be on the editing of the design.

End! (Feiss, 1997)



Figure 6-1. Cow and Chicken.

Above, the desire to experiment with 3D display techniques has been expressed based on the mismatch between the display of 3D content on a 2D display. This was partly caused by the fact that the Cubby project (Djajadiningrat, 1998) has been running parallel to this project for most of the time. The head-coupled display of Cubby can be combined with the two-handed system used in this research and in fact, a project such as Cubby+ has already been started. With this combination, we hope to continue the search for innovative support of the designer.