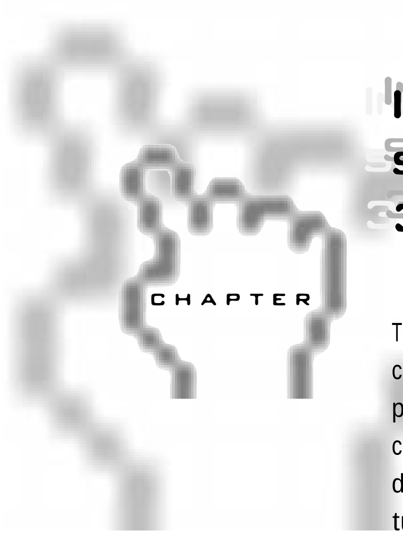


Introduction to computer-supported conceptual 3D modeling

This chapter introduces the use of computers as an aid to the form creation phases of design. In the conceptual phase of the design process (Roozenburg & Eekels, 1991), the industrial designer is concerned with the generation of ideas and concepts for the development of products. Although the conceptual phase constitutes only a short period in the product development process, it has many important implications for the later phases. Traditionally, designers sketch, make collages and models in the conceptual phase. Regarding modeling, designers choose from a wealth of techniques, tools and materials. Although the computer is widely used in the design process, it is usually not used in the conceptual phase. Often, the traditional modeling techniques are preferred over computer systems. In this chapter, it is argued that the nature of interaction with the computer is an important factor in determining its suitability for conceptual modeling[1]. When working with clay, for example, a designer can use both hands and work directly with the form. With most computer systems however, the designer can only use a mouse, which limits the interaction with the model to sequential single-handed movements in two dimensions. The purpose of this work is to address the discrepancy between modeling with the traditional tools and computer supported modeling.

In this chapter, the need for computer support of conceptual modeling is asserted first. After evaluating the traditional modeling techniques, the benefits of computer support are established. Additionally, a computer system is only useful if it meets the requirements of the designer in the conceptual phase and these are listed. The interaction with current computer systems is evaluated to find that the current systems limit the designer in his interaction with the model. The desktop configuration of most CAD (Computer Aided Design) systems prevents the designer from applying skills acquired in working with traditional tools and materials. Then, possibilities for enhanced interaction with CAD systems are

[1] In this work, the term conceptual modeling refers to the creation of form during the conceptual phases of the design process.

Figure 1-1. When modeling with clay, both hands can be moved freely.

explored. An examination of experimental systems shows that there are alternatives to the desktop configuration of CAD systems.
After that, the development of an interaction device for use with the non-dominant hand is presented. This device, called the Turntable, indicated the value of two-handed interaction with CAD systems.
In addition, after evaluating two-handed operation with a mouse and the Turntable, the decision was made to pursue research in two-handed operation of CAD systems with 3D interaction devices. This was also motivated by previous studies on the practice and behavior of designers and the examination of experimental systems.
Lastly, the structure of the research is explained. Four steps were taken over the course of the project: an explorative, an investigative, a constructive and an evaluation phase. These steps are reflected in the subsequent chapters of this work.

1.1 The potential of computer support of conceptual modeling

The first question that may arise is whether there is need for supporting conceptual modeling with computers. If CAD[2] systems do not have benefits over the traditional tools, there is no incentive for designers to use them. Therefore, an overview of the use of the conceptual modeling process is given with attention to the benefits CAD systems have over traditional tools. In addition, requirements are presented for CAD systems that support conceptual modeling.

Traditional tools and computer tools are not mutually exclusive.
In graphic design, traditional tools and materials such as brushes and paper are combined with computer tools with the aid of scanners and printers. The advent of inexpensive 3D scanning and printing tools could promote the same combined use of traditional and computer tools for conceptual modeling. Technologies for exchanging 3D object geometry between the real world and the computer have been around for some time. However, 3D scanning and printing used to be costly and difficult to maintain and operate. The achievements made in this area could mean that these tools become as ubiquitous as 2D scanning and printing technology. This would present a new view on the role of CAD systems in conceptual modeling. A design shape could evolve in steps alternating between development with traditional tools and CAD systems, each being chosen for its optimal use. In this situation, CAD systems do not

[2] In this work, the term CAD (Computer Aided Design) is used in its broadest sense and includes systems known as CAID (Computer Aided Industrial Design) and CACD (Computer Aided Conceptual Design) systems.

need to offer all the functionality of traditional tools and more. However, the 3D scanning and printing techniques have not matured yet. In addition, the tools provided by computers should meet the practice of the designer in the conceptual phase. Therefore, there is still ample reason to explore how CAD systems should support the designer in conceptual modeling.

1.1.1 The use of conceptual modeling in the design process

The design process can be divided into different phases. In literature, several models of the design process can be found. Most models identify different phases but they show the same basic activities and the same sequence of those activities (Roozenburg & Eekels, 1991). The first phase is the analysis of the problem resulting in a description of wishes and demands for the product. Conceptual design comes after the analysis and is often regarded as the creative phase (Muller, 1997). Usually, several concepts are generated as different solutions to the goals set for the product. In the conceptual phase, the designer is often going through a number of synthesis and analysis phases. In synthesis phases, the design space with possible solutions is explored, while in analysis phases, the concepts are evaluated against the goals. Generally, materialization of concepts gets more detailed and finalized gradually.

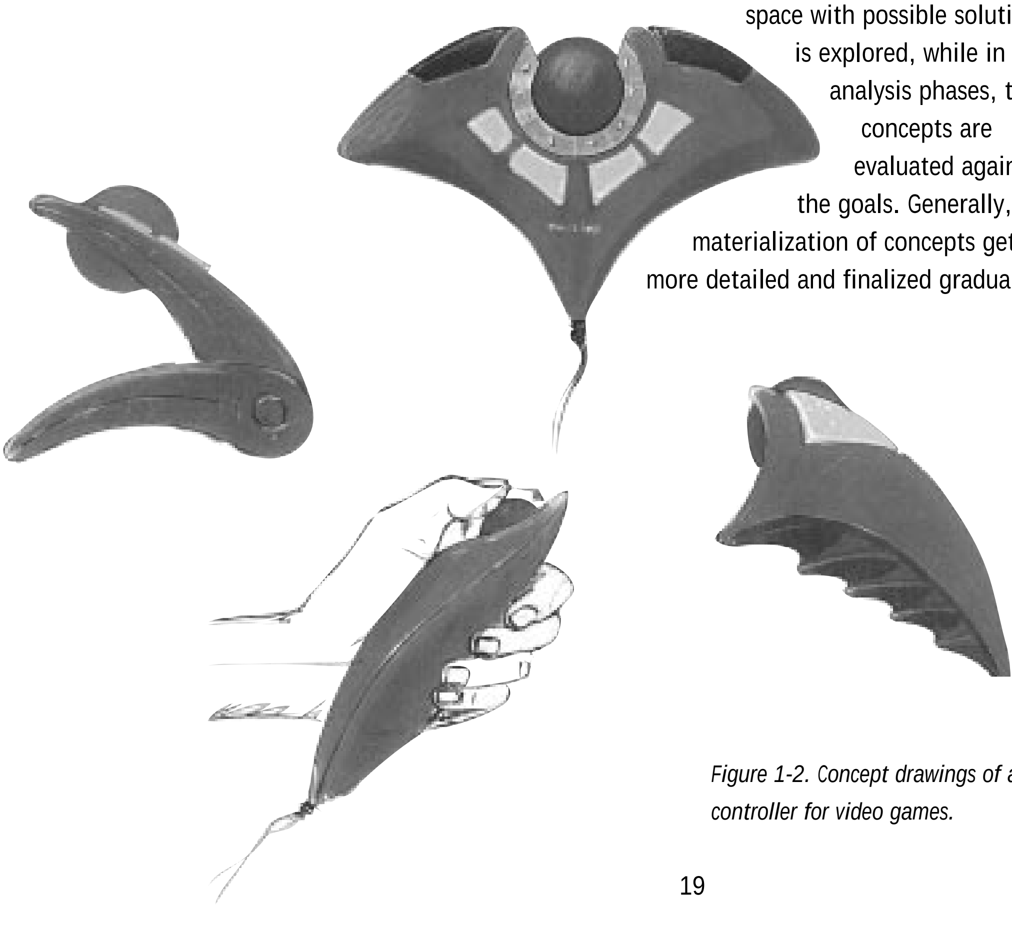


Figure 1-2. Concept drawings of a controller for video games.

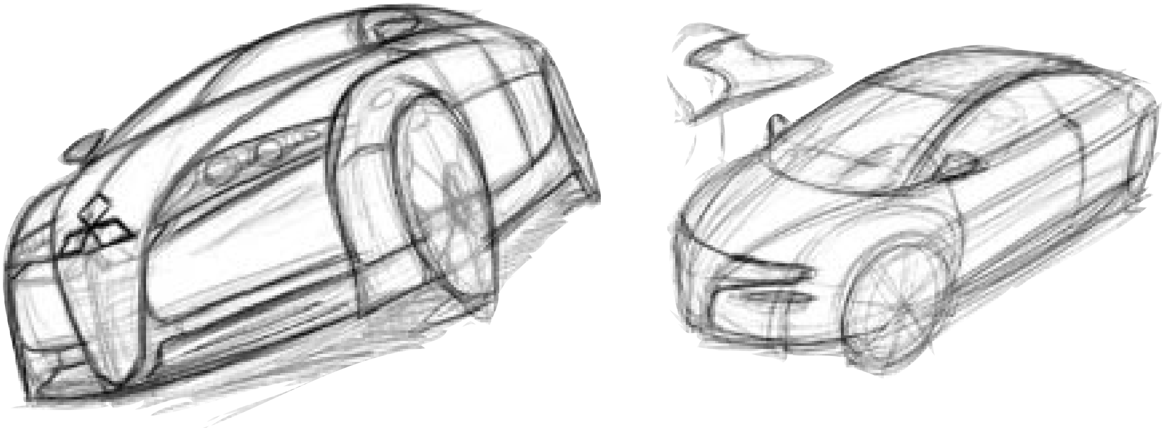
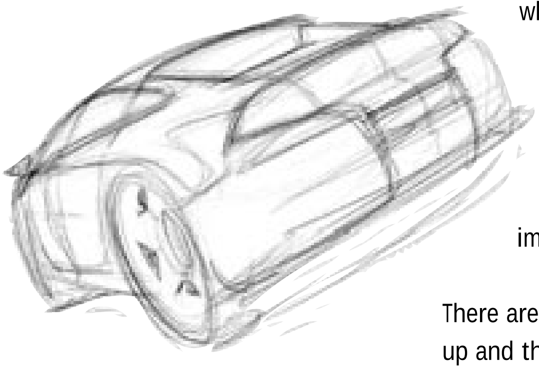


Figure 1-3. Sketches of a concept for a car.

Sketching and modeling are techniques industrial designers use to create, evaluate and modify product concepts. They are not only the means of externalizing the ideas a designer has about the form of a concept but also the means of applying “visual thinking” (Tovey, 1989). Sketches and models are not just representations of the concept before the start of the sketching or modeling session.

While sketching or modeling, the designer is actively designing; the concept changes while sketching or modeling because the evolving design might spark new ideas. Especially with sketching, the activity is interwoven with the generation of ideas. In indecisive periods, designers typically doodle or make sketch-like movements with their hands without actually drawing with the hope of triggering a new idea. The importance of the combination of mental and motor processes, or manipulospatial activity, has been recognized in research on industrial design (Tovey, 1986).

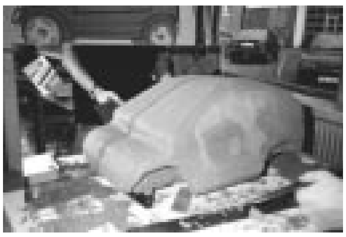
Sketching is considered an ideal tool for fast generation and evaluation of concepts because of its close relationship with the creative process. One of the benefits of sketching is that the open nature of the sketches allows the designer to reinterpret the depicted concept, something more difficult with modeling. Modeling is more involving but appropriate and sometimes essential for the evaluation of complex 3D shapes. The practice of the designer shows that sketching and modeling are complementary and that they both serve a purpose in the conceptual phases of the design process. During the process of form creation, a designer will often break from his sketching in order to make a quick model. These models are done in order to test and confirm various visual and tactile aspects of the form. This activity is also a sort of 3D sketching in



which alterations and improvements are made using very simple materials. The feedback about the shape that the designer obtains is amplified by the fact that he uses both hands in this process and, through these actions, the coupling of his mental imagery with the 3D model are made. For form creation, quick model making is an important activity.

There are two general approaches to quick modeling: the building up and the carving away approach. When building up, a designer typically builds models up out of planar pieces cut out from paper, cardboard or thin styrene plastic. These pieces are taped or glued at the edges to form a rough 3D shape. Foam is sometimes used to fill in larger areas and, for greater rigidity, foam-core board is often used. When carving away, on the other hand, the designer usually starts with a solid material such as foam or clay from which parts are cut away or reshaped by hand using simple tools. It is also possible to insert other materials and/or components into the final soft shape.

There are important reasons why these techniques are used by the designer. The sculpted models of the carving away approach give a quick impression of the shape of the object and are primarily used for form study and ergonomical considerations. The design of hand-held products for example, is difficult without creating sculpted models in an early stage. If worked carefully, extremely refined shapes are possible. The architectonic models produced with the building up approach, on the other hand, are crude in their shape definition but afford a hollow interior into which mechanisms or electronics can be fit and tested.



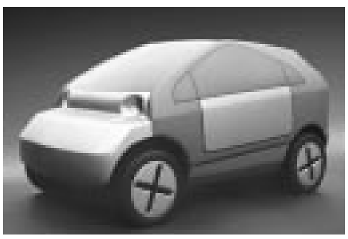


Figure 1-4. Model of a car concept in different stages of development.

For the design process in the automotive industry, the use of traditional modeling has been described extensively (Tovey, 1992). Tools and materials used for modeling are almost identical among car-design studios. For instance, most studios use one particular kind of clay for modeling. The labor-intensive process of making scale models of cars is undertaken by a team of trained modelers. This is different from the practice of most other industrial designers. They usually create models themselves and use whatever materials and tools are available or convenient. In addition, modeling is often used in short periods, alternated with other activities.

Figure 1-5. When modeling with clay, the designer can use a variety of tools.

Designers are known to use a wide range of materials, such as clay, wood, plaster, cardboard and foam. In most cases, specialized tools are used and for each material, a different set of tools is available (Shimizu, Kojima, Tano & Matsuda, 1991). Figure 1-5 presents a set of tools used for modeling with clay. It shows that the designer can use a variety of tools for working with one material. Each of the tools is optimized for its intended action. The shape of the handle for instance, is optimized for the grip used to hold the tool and the movements it will make. For fine and precise movements, the designer can use tool that is held between the fingers. Tools held in the whole hand provide a stable grip and they can be chosen for actions that need appliance of force. These tools fit close to the designer's body and allow for skilled manipulation.

1.1.2 Benefits of computer support

Integration with other CAD systems

Some of the potential benefits of using computer support for conceptual modeling are immediately apparent. Computer support of the conceptual phase can promote integration with the later phases of the design process because there, the computer is frequently used for activities such as finite element analyses for stress analysis and Computer Aided Manufacturing (CAM). Therefore, when traditional tools are used to produce physical models out of clay for instance, the models need to be imported into the computer for use with CAD systems. This digitizing process takes time and is open to interpretation faults. When CAD systems are introduced earlier in the process, the digitizing step is unnecessary because the model is already present in digital format. This saves time and prevents the digitized model from differing with the intentions of the designer (if the optional conversion from one CAD system to the other does not degrade the model). Redesigns amount to a significant proportion of all design problems. For redesigns, it is convenient for the designer to be able to use the models of the original design as basis for the new design. With CAD systems in the early phases of design, the finalized previous model can be easily reused. With physical models, this is more difficult (although commonly done). Often, the original models cannot be used, either because changes were made to the computerized version of the model later in the process or because the original models are not available anymore.

History of the design

Another benefit of CAD systems is that the designer can preserve the development of a design. The designer can review previous stages of a model in development and decide to change an earlier decision and continue work from that point. This kind of functionality is difficult to realize with traditional modeling tools. Computerized geometry also allows for the fast evaluation of different variations on the same design because generating copies of a design is easy. Combined with the fact that surface materials and lighting conditions are easily applied, the evaluation of the surface materials can be more conveniently done.

Sharing the design

The geometric representation of a CAD model is easily stored and distributed by electronic means. Therefore, the design can be transferred to distant locations. This not only means that the design can be sent anywhere but also allows for simultaneous access to the same design from different locations. An increasing use of shared design tools can be seen that employ the Internet for the evaluation and/or modification of designs.

Freedom of form

Computer-supported modeling offers the possibility to create designs without the limitations of real world materials and tools. Although the final form of a design is constrained by the manufacturing process, the development of the design need not be constrained by these conditions. CAD systems can increase the amount of freedom for form expression and allow the designer to think of forms that are more expressive before considering the limitations of the manufacturing process.

Working in different scales CAD systems allow the designer to work in different scales. With a CAD system, it is as easy to work on tiny details as it is to work on the overall shape of the design. With most CAD systems, the view on the model is easily changed and the designer is allowed to switch between a zoomed in view on a detail and an overall view with ease. When zoomed in, manipulation can be done with much higher precision. With traditional tools, the designer is limited to work with a model of approximately the size determined by the scale chosen at the start of the modeling session.

Dynamics The use of the computer promotes the communication of the dynamical aspects of a product in an early stage of the development. With physical models, it is often difficult to prototype and to communicate how users are supposed to interact with a product. Lately, authoring tools have become available that allow designers to simulate interactive aspects of products. With these tools, static or interactive presentations can be used for product evaluation before a physical model is built.

1.1.3 Requirements for computer support

The benefits of CAD systems might suggest that there is every reason to use CAD. However, the current CAD systems do not match some of the important benefits of the traditional tools for conceptual modeling. These benefits of traditional tools become requirements for CAD tools if they are to become a more viable alternative.

Using the skills of the designer Designers have invested a lot of time in acquiring the necessary skills to use the traditional tools. In the automotive industry for instance, modelers have trained for years before they start working at design departments. The amount of skill acquired has the result that the designer has become fluent with the tools. This allows him to convey his desired expression of the product via the model. Current CAD tools do not replace those possibilities. It seems necessary that CAD systems allow some of that skill to be supported before designers decide to use a computer for modeling.

Thinking style ***"Dammit Jim, I'm a designer, not a mathematician" (Westin, 1998)***
CAD systems should reflect the way designers think. Above, it was shown that the creative process of designers is interwoven with the motor processes active in sketching and modeling. To support the

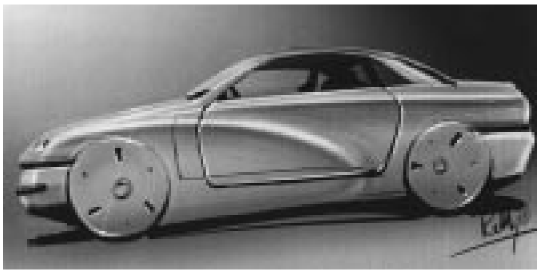
designer's thinking style with computers, designers should be able to apply the same form of visual thinking. The thinking style of the designer is not mathematical, especially in the conceptual phase. Therefore, CAD applications should hide their underlying mathematical structure from the designer. Adherence to the designer's thinking style also implies that CAD systems should allow for shapes that evolve from unspecific to defined forms gradually. This is a challenge for most CAD systems because the underlying mathematical structure generally requests precise specification of geometry.

Ease of learning

Like any product, a CAD system should be easy to learn and easy to use so that the designer can become fluent with it in a short time (Green, Liang & Shaw, 1995). On the other hand, it is not fair to expect that there should be no learning curve at all. Furthermore, making a tool easy to use may lead to a restriction of its potential power. A compact camera for instance may be easy to learn and easy to use but it is not very versatile. A professional camera on the other hand is more difficult to learn but once mastered, offers the photographer much more freedom in taking pictures. The optimal situation seems that the CAD system is easy to learn so that the designer can start using it right away. Then, if the designer is becoming familiar with the system, the system should allow the acquired skill to be transferred to modeling operations that become more powerful. In other words, novice users should be able to become expert users gradually thereby advancing design skills instead of computer skills.

Personal style of the designer

When debating the use of CAD systems, designers and artists often express their concern about the possible loss of their personal style. In learning to work with the traditional tools, designers have developed a personal touch that distinguishes them from other designers. They feel that the traditional tools allow them to convey this style better than a computer tool would and complain that most computer-generated artwork is uniform. In the opinion of the author, that is not necessarily caused by the use of the computer but rather by the current state of the CAD systems and software. Some evidence for this can be found in the developments of 2D computer-based sketch tools. The latest generation of sketch tools, such as Painter by MetaCreations and StudioPaint 3D by Alias|wavefront, allows users to sketch with a stylus on a graphics tablet. The tilt, pressure and speed applied on the stylus are used to influence



the characteristics of the strokes dynamically.
In combination with software that simulates real-world tools, sketching with the computer allows the user to use his/her ability to sketch and to preserve a personal style (Figure 1-6). It is hoped that new tools will allow this to occur in 3D computerized form generation.

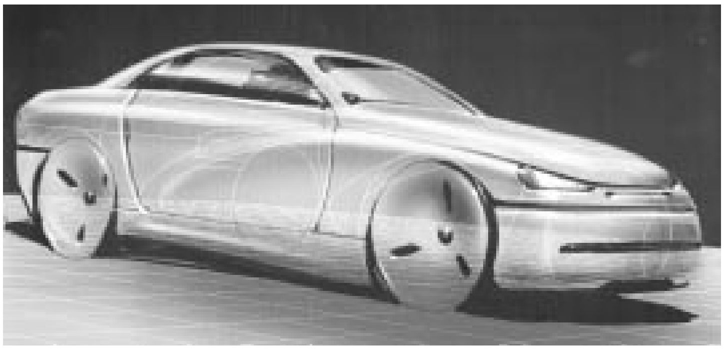


Figure 1-6. Sketches of a car concept made by drawing with Painter over a wireframe generated in a 3D CAD program.

1.1.4 The use of computers for conceptual modeling

In the conceptual phase of the design process, designers choose from a wealth of materials, tools and modeling strategies. Modeling is an active creative process in which the form of the design is evolving. It is therefore important to realize that tools for conceptual design should be low profile so that the designer can concentrate on the design instead of on the tool. The train-of-thought and flow of ideas should not be interrupted. The training and skill of designers has made them so fluent with the traditional tools that these have become medium instead of a barrier. The challenge is to create computer tools that can be used with the same level of fluency.

CAD systems have potential for conceptual design, yet the use of CAD systems for this purpose is limited. This brought forth the observation that for sketching, it is still the age of the continuing reign of PAD (Paper Aided Design)[3] (Stappers & Hennessey, 1999). CAD systems have become affordable to even small design offices. It seems sound to conclude that the absence of computers in conceptual modeling is due to the characteristics of the tools and not only caused by pragmatic reasons such as their price or the unfamiliarity of designers.

[3] Since computers are even less used for conceptual modeling, the acronym CAD might be better called "Clay Aided Design".

1.2 Interaction with conventional CAD systems

Next, a brief overview is given of interaction issues of conventional CAD systems because these could be responsible for the low penetration of CAD in conceptual modeling. The majority of CAD systems consist of a conventional desktop computer combined with a CAD application. Currently, CAD systems are mainly used in the later stages of the design process when the form of the design has already been formalized. At this point, the design is easily entered into the computer and the resulting geometric model can be used to evaluate the concept. Evaluation can have many aspects such as the simulation of dynamic properties, the calculation of stress analyses and the creation of images and animations for product presentations. The evaluation is the phase in which computer support is given the most credit. The question is why CAD systems are so little used for conceptualizing the form of a design even though using a computer has advantages as argued above. To address this question we will present how the configuration and the application influence the interaction with CAD systems.

1.2.1 Hardware considerations

The desktop configuration of conventional CAD systems (mouse, keyboard and screen) was developed back in the sixties (Engelbart & English, 1968) and has been optimized over the previous decades. However, it did not radically change as can be seen by comparing an early prototype (Figure 1-7) and a contemporary system (Figure 1-8). What did change was the fact that technological developments have caused a dramatic increase in performance of computer hardware while prices dropped at the same time. The result is that most consumer computers are now capable of running CAD applications. It should be noted that the developments concentrated on improvements of the processing unit part of the computer hardware and not

Figure 1-7. Early prototype of a computer with a desktop configuration.

Figure 1-8. Contemporary computer with a desktop configuration.

Figure 1-9. Graphics tablet with a puck.

on the input and output media. The standard desktop configuration still provides a 2D screen for evaluation and a mouse and keyboard for interaction with the computer. However, some systems provide additional interaction devices such as graphic tablets with a stylus and/or a puck (Figure 1-9).

1.2.2 Software considerations

Interface Developments in user interfaces have evolved from the early command line interfaces towards the current graphical user interfaces. Not much over a decade ago, geometry was usually created and manipulated by typing commands, a very indirect way of interaction. Currently, the state of the art in CAD systems offer mouse controlled interfaces that allow "direct manipulation" (Schneiderman, 1987). The term direct manipulation is often used to describe the ability to manipulate graphical representations of objects on the screen with the mouse interactively. Over the years, nearly all user interfaces of CAD systems have become direct manipulation interfaces of the WIMP (Windows, Icons, Menus, Pointing device) type. In combination with the common desktop configuration of the computer, the widespread adaptation of the WIMP interface makes the basic interaction with CAD systems uniform. CAD applications can be differentiated in the way they represent the models internally and in their use of direct manipulation to create and manipulate the models.

Representation of geometry Not so long ago, modeling programs could be divided into three categories. The first CAD applications used line segments to represent 3D models (wireframe modelers) but these applications are not commonly used for conceptual modeling. The second group of applications uses surface descriptions for the representation of geometry (surface modelers). The third type (solid modelers), use volumetric descriptions for the geometry. The type of representation determines the way in which a designer can manipulate the model. As introduced above, designers typically use two approaches for building physical models: building up and carving away. Two types of CAD systems correspond to these approaches. Surface modeling represents the building up approach. Different parts of a design are cut out of cardboard, for instance, and assembled to make the final shape. Solid modeling resembles modeling with foam and clay where material is added and subtracted to arrive at the final shape. Lately, the strict division is blurring as hybrid modelers have been developed that allow a designer to represent a model either in a surface description or in a volumetric description or as a hybrid of both descriptions. In addition, the description of a model need not be static since the possibility exists to exchange objects between surface and volumetric descriptions.

Modeling techniques An inventory of modeling techniques in CAD applications is not easily made. For one, there is a plethora of operations for creating and manipulating geometry. Boolean operations for example, allow the modeler to add and subtract parts of the model. Sweeps can be used to create objects by moving a profile along a path. Secondly, the modeling techniques are heavily dependent on the internal representation of the model. Interaction with polygonal surfaces, like meshes for example, is completely different from interaction with smoothly curved surfaces like B-splines. With meshes, vertices and faces can be moved while B-splines are generally manipulated through abstract control points.

1.2.3 Problems of interaction with conventional CAD systems

As stated before, the quality of the interaction with conventional CAD systems is determined by both the hardware and the software. The interface techniques of the current applications are unavoidably interwoven with the use of the mouse as input device and the screen as output device. It is almost as if the designer has to create a form holding a bar of soap while looking at a television screen. Compare this to the traditional tools that provide a full stereo view and haptics for evaluation of the model and manipulation with both hands directly in 3D so that all motor-skills can be utilized by the designer (Figure 1-1). From this comparison, it is apparent that CAD systems fall short in supporting the designer's skills. The standard desktop set-up offers an amount of expression to the designer that is only a faint reflection of the expressiveness of models made with traditional tools.

Another problem is that the direct manipulation interfaces are not as direct as the traditional tools. For example, when a surface of revolution is created in a modeling application, the user typically selects an axis of revolution, indicates the profile to revolve, and like magic, the surface appears. When the result is not as expected the shape of the profile needs to be changed and the procedure is repeated. This stepwise process is characteristic of CAD applications but not of traditional tools. With a potter's wheel for instance, the user is constantly manipulating the surface of the object while observing the changes in real time. Here, an iterative process gradually gravitates towards the desired form.

Conventional CAD applications fall short in supporting the designer's way of modeling. Instead, the modeling techniques reflect the internal representation and software algorithms of the application. For example, Kolli and Stuyver evaluated CAD systems for conceptualizing product form in three phases, based on a method of conceptual design (reported in Hennessey, 1994). In the first phase of the evaluation, designers were asked to arrange several functional parts of a product into different combinations. The study revealed that CAD programs failed to support the simple rearrangement task. In the second phase, the designers were asked to take one of the combinations and modify them by adding rounded corners for instance. The second phase was badly supported too. In some instances, the modifications forced the designer to rebuild the original shape because the desired result could not be achieved with the original model.

The conclusion is that hardware and software are both responsible for a mismatch between the skills of the designer and the present CAD systems. The hardware forms a barrier since the input devices prevent the designer from applying all of his motor skills.
In addition, the computer screen as output device limits the designer in the evaluation of and the interaction with the design. The software distracts the designer from his task of modeling and confronts designers with modeling techniques based on the underlying mathematical structure of the model. Since the CAD applications are so dependent on the hardware they are used on, it is not easy to just substitute the input and output devices.
To enhance the interaction with CAD systems, it seems inevitable therefore to consider both aspects simultaneously. In the following discussion, the capabilities of the designer are put first by looking at alternative means of input and output. The consequences this has for the software are dealt with later.

1.3 Enhancing interaction with CAD systems

Above, it was concluded that the interaction with CAD systems forms a bottleneck. It is now shown how the use of alternative hardware can improve the interaction with those systems. The standard desktop setup has become widespread to a point that interaction researchers and CAD developers tend to forget that there are alternatives. When interacting with CAD systems, the model is manipulated with input devices and the result of the manipulation is evaluated with output devices. The input and output devices both influence the quality of the interaction with a CAD system. Below, alternatives are indicated for the mouse as input device and the computer screen as output device. In a small number of commercial and in some experimental systems, these alternative forms of input and output have been applied. Examples of such systems are given and how these systems apply alternative means of input and output to enhance interaction is indicated.

1.3.1 Input devices

Replacing conventional interaction devices

The use of the mouse in the standard desktop setup imposes a limit to the degree of interaction that a user can have with the system. The mouse registers only planar displacements. It cannot be used to register gestures in 3D and therefore, manipulation with the 3D model is often hampered because intended 3D manipulation cannot be accomplished directly. Substituting the mouse for a graphics tablet with a stylus allows for sketch input. Although the stylus position is still sensed in 2D, the use of sketch input allows for new forms of interaction more suited for conceptual modeling as shown by the Fast Shape Designer system developed at our faculty (van Dijk, 1994). Other devices determine a position in three dimensions, sometimes in combination with rotational degrees of freedom so that both the position and the orientation of the device are measured. An example of such a device is the 6D Mouse, shown in Figure 1-10. With a glove such as the CyberGlove in Figure 1-11, the position and orientation of the user's hand and in addition, the bend of the

Figure 1-10. The 6D Mouse of which both position and orientation are sensed.

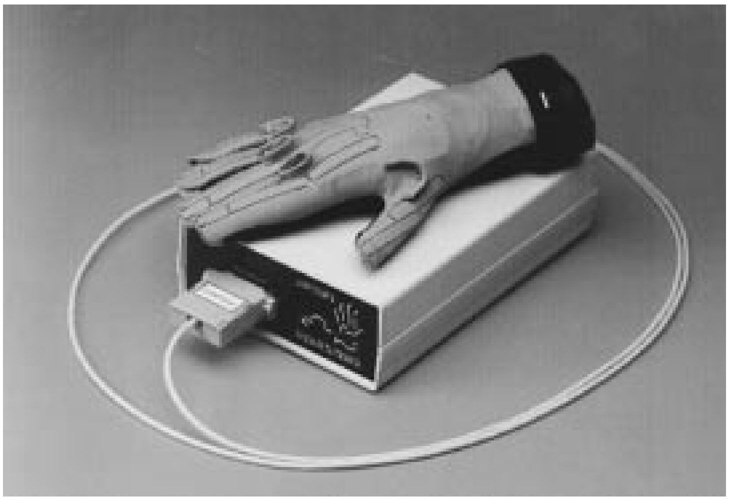


Figure 1-11. The CyberGlove measures the position and orientation of the hand and the bend of the fingers.

fingers is registered. Such devices can offer the designer a way to work on the 3D model faster and with more control.

Using multiple interaction devices In the standard desktop setup, the mouse and keyboard are the only interaction devices. The mouse is used for operating lot of different tasks in succession. Instead of using a computer with one device, a situation can be imagined with multiple devices, each device designed for a specific task. Then, the user can select the device that is most appropriate for the task at hand. The presence of multiple devices on a system also promotes the use of two devices at the same time, one specifically for each hand. In most CAD systems, the use of the second hand is often restricted to pressing some dedicated function keys on the keyboard. The system is generally operated with one hand only, caused, to a large extent, by applications that do not support the use of multiple interaction devices.

1.3.2 Output devices

Improving visual output Current computer systems are able to produce high quality images of computerized objects with high refresh rates. This enables a designer to manipulate the computerized design in real time with a realistic view. However, with the standard desktop configuration a designer is unable to evaluate a computerized model as he does with a physical model because the display is 2D. To provide the designer with enhanced visual feedback, some systems provide a stereo view of the model or simulate movement parallax while other systems combine these two. A stereo view can be provided with different technologies that have different implications for working with the system.

Systems that present a stereo view need to display two different images to the user, one for each eye. This can be realized in a number of ways of which the most popular ones follow. First, a standard monitor can be used in combination with glasses that route the correct image to each eye. Shutter glasses and polarized glasses are commonly used for this purpose. Second, two displays, mounted close to the eyes of the user, can be used to generate separate images for each eye. The most familiar examples of this method are the helmets or the visors frequently used in VR systems. Third, with auto-stereoscopic systems it is possible to generate a stereo image without the need to wear glasses or helmets.

A number of technologies exist to realize auto-stereoscopy such as systems with specialized display techniques (e.g. holographic systems, volumetric laser displays) or systems with dedicated monitors (e.g. monitors with Fresnel lenses).
The method with standard monitors and the two-display approach are the most popular but they require a designer to wear glasses or helmets while working with the system. Auto-stereoscopy does not have this disadvantage and has the convenience that the display of spatial information is not limited to one person. Nevertheless, auto-stereoscopic systems are not widely used, either because they are still experimental or because of their high costs.

Some systems offer the designer the possibility to view objects stored in the computer from different angles. With systems known as Fish-Tank systems (Ware, Arthur & Booth, 1993), a standard monitor is used and the position of the head of the user is measured. The measured head position is used to produce images with a perspective view corresponding to the current position of the user. The head-coupled display can produce the effect that computerized objects appear to come out of the screen because movement parallax makes close objects move differently than objects further away. Recently, head-coupled display technology has been taken further in the Cubby system, shown in Figure 1-20 and Figure 1-21 (Djajadiningrat, 1998). In this system, three orthogonal screens are used instead of one monitor. The use of three screens increases the notion of depth and offers the possibility to present the objects completely in front of the screens. Head-coupled displays are only effective when the viewpoint of the user varies because with a static viewpoint, the illusion of a spatial display is not realized.

Figure 1-12. A user wearing a VR visor.

In some systems, both stereo vision and movement parallax are supported to present images with the correct perspective to the user. The most common examples of such systems are immersive VR (Virtual Reality) systems in which a user is immersed into a virtual reality. In most immersive VR systems, a visor or helmet (Figure 1-12) is used to present spatial display to the user. Both the position and the orientation of the head of the user are established by sensing the position and orientation of the visor or helmet in which the two images for each eye are displayed. Another example is the CAVE (Figure 1-13) in which images are projected on walls and some-

Figure 1-13. A user in a CAVE.

times the floor and/or ceiling of a room. An overview of these and other techniques and the implications for manipulation in these virtual environments is given by Buxton and Fitzmaurice (1998).

Using haptic output

When compared to visual feedback, haptic feedback is not often applied. However, haptic feedback can help to evaluate the surface features of a model, especially for models where ergonomic aspects are important such as models of handheld products. Some interaction devices integrate sensing with force feedback such as the Phantom device (Figure 1-14) and the CyberGrasp glove (Figure 1-15). These devices can be used for evaluation of the shape of models but not many systems employ such devices for haptic feedback.

Figure 1-14. The Phantom interaction device with haptic feedback.

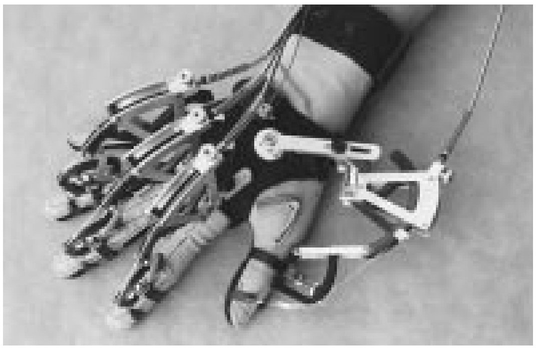


Figure 1-15. The CyberGrasp glove with haptic feedback.

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Physical output It was already noted that the creation of physical hardcopies from computerized geometric models is becoming affordable. Most rapid prototyping techniques are of incremental nature and create models layer by layer. Conventional machining techniques are mostly associated with the creation of high precision metal objects. However, they can be adapted to fast machining of light material, thus making them suited for rapid prototyping (Tangelder, Vergeest & Overmars, 1998). The physical models present the designer the possibility to touch the model and evaluate its shape (Figure 1-16). However, the generation of a hardcopy is time consuming and not yet as cheap as a print on paper. Therefore, the designer is not likely to produce many hardcopies during the design process. In addition, the physical models are snapshots in time and not useful during the actual modeling of the design when the design is manipulated.

Figure 1-16. Creating a hardcopy of a side-view mirror with NC machining.

1.3.3 Examples of experimental systems

The 3-Draw system is an example of a system with enhanced input (Roberts, Sachs & Stoops, 1990). The 3-Draw system is a CAD system with a standard computer screen for fast creation of shapes. By using two devices, a user can create wireframe models with two hands, directly in 3D. Another CAD system with two-handed 3D input and a standard screen is the THRED system in Figure 1-17 (Shaw & Green, 1994). With this system, free-form polygonal surfaces such as a terrain can be created. In THRED, the second hand is used for a number of operations including the control over the position and orientation of all the objects in the scene, like in 3-Draw.

Figure 1-17. The THRED system with two-handed 3D input.

For the application area of neurosurgical planning, the Netra system shown in Figure 1-18 has been created (Hinckley, Pausch, Goble & Kassell, 1994b). The system is operated with two hands and the user can choose from differently shaped devices (props) to indicate cross

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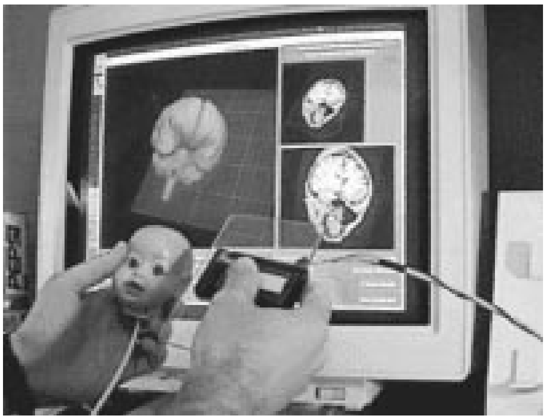


Figure 1-18. Two-handed 3D input with props devices.

sections or trajectories in 3D medical data sets. In the figure, the doll-shaped device is used to orient the brain on the screen while the other hand indicates the desired cross section.

Cubby has been introduced as an example of an advanced head-coupled display but it also allows manipulation with displayed objects (Figure 1-20 and Figure 1-21). It does not offer stereo images to a user but due to the use of the three orthogonal screens, the user gets the impression that objects are projected in front of the screens. This facilitates manipulation with the objects displayed because a user can reach into the scene and interact with the objects directly. In an experiment with Cubby, three-dimensional manipulation in the display area was accomplished with a single pen-shaped device.

SmartScene[4], shown in Figure 1-19, is one of few commercial immersive VR systems for assembly of virtual scenes and simulation (Multigen Inc.). The use of a VR helmet presents users of SmartScene with a stereo and head-coupled view. Manipulation with objects in the scene is accomplished with two gloves. The disadvantage of the immersive situation is that the user is shut off from the real environment. This makes interaction with co-workers difficult and deprives the user of stimuli in his environment such as sketches, collages and the coffee mug, of course.

[4] SmartScene is formerly known as SmartModel.

Figure 1-19. A user working in VR with MultiGen SmartScene.

Figure 1-20. A user manipulating in Cubby.

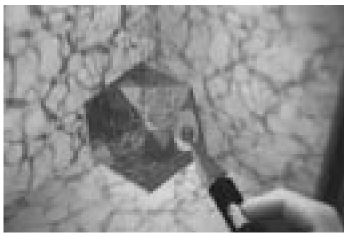


Figure 1-21. View of the user manipulating in Cubby.

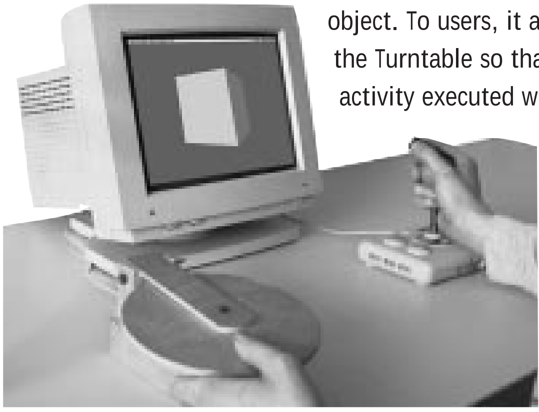
Most of the experimental systems presented allow a user to work with both hands, directly in 3D. This is not supported in conventional CAD systems but common in working with traditional tools. When modeling with clay, for instance, one hand positions and stabilizes the model while the other is used to perform actions on it. This kind of two-handed interaction is typical when working with workshop and household tools.

1.4 The “Turntable and Grabber” system for use with both hands

Before introducing the research questions, another experimental system is introduced. The Turntable and Grabber system was conceived at the beginning of the IDEATE research project as part of a computer system supporting 3D modeling with two hands. The research on this system was the starting point of the research project described in this work. Starting as an explorative study into the development of a tool for conceptual modeling, it gradually developed into formal studies of two-handed interaction with computer systems. At the end, it became clear that profound research into the nature of two-handed interaction in 3D was necessary for which the Turntable could not be used. However, it is felt that the Turntable as an interaction device is still innovative and useful. The design of the Turntable represents a specialized approach not commonly found among interaction devices.

Based on protocol studies by Kolli and Hennessey (reported by Hennessey, 1994) it was noted that creative people use both hands for most modeling activity. Since none of the available CAD systems provided two-handed operation, a system was developed to experiment with two-handed operation of 3D computerized modeling. Two interaction devices were designed to explore the use of two-handed operation for offering a richer and more efficient type of interaction. Inspiration for this system came from experimental systems like 3-Draw (Roberts, Sachs & Stoops, 1990) that offers two-handed creation of spatial form.

Figure 1-22 presents the system that was created. Two different input devices were designed for specific use with each hand. The Turntable device utilized an analogy with the potter’s wheel. The user can spin and tilt the disk to spin and tilt the computerized



object. To users, it appears as if the object is placed on the Turntable so that their attention can remain on the activity executed with the other hand. With the Grabber device, the user can grasp and move points on an object by pinching the device with the thumb and index finger. The Grabber is an ergonomically shaped controller on top of a modified joystick. In the design of both devices, a high degree of intuitivity for the form was determined by the gestures used to operate them. Three-dimensional manipulation can be achieved when the two devices are used in conjunction. The user can rotate the object with one hand while the other hand is free to grab points on the object and move them.

Figure 1-22. The top picture shows the simultaneous use of the Turntable version 1 (left picture) and the Grabber (right picture).

Observations of users operating the system indicated a clear potential for the application of two-handed operation in computer aided modeling (Hennessey, Gribnau & Stuyver, 1995). The Turntable was easy to use and there was no difficulty using the device with either hand. Criticism of the Turntable device focused on the fact that it was hard to tilt (without clamping it to the table) and that the hand could not rest on the disk. The Grabber showed poor performance, mainly due to the limitations of the joystick design. It was set aside for later development.

1.4.1 Development of the Turntable

The shortcomings in the design of the first Turntable prevented it from being used in the evaluation of two-handed operation of 3D modeling. Version 2 of the Turntable, shown in Figure 1-23, was developed to address these limitations. The tilt axis was moved to the center of the device making it possible to rest one's hand comfortably on the disk. In addition, the design of version 2 allowed both the spin and tilt rotation axes to be operated equally comfortable. Still, version 2 had shortcomings that were exposed in preliminary testing of the device. To keep costs low, the Turntable used optical sensors of a mouse and therefore, it did not measure the angle of the disk absolutely. Instead, it measured the changes in orientation and mismatches occurred when the measurement errors accumulated over time. The problem was the impossibility to reset mismatches between device and object on the screen.

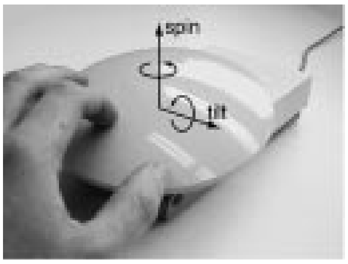


Figure 1-23. Turntable version 2.

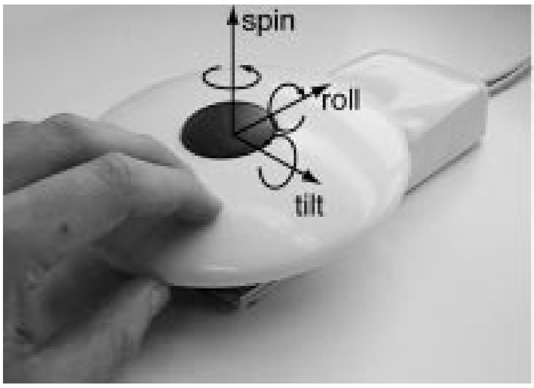


Figure 1-24. Turntable version 3.

A third version of the Turntable was developed to address the mismatch problem, the limited tilt angle, and the fact that only two rotation axes were measured. The last issue prevents users from specifying arbitrary orientations in a single gesture. Instead, users are forced to decompose an intended arbitrary rotation into sequential rotations over one or two axes. The decomposition is disadvantageous for optimal performance and requires additional attention from the user as shown in previous research (Hinckley, Tullio, Pausch, Proffitt & Kassel 1997; Djajadiningrat, Overbeeke & Smets, 1997). The introduction of the extra axis was a deviation from the original goal of the Turntable because the limited tilt angle and the two rotation axes were intentionally part of the design of the previous versions of the Turntable. The main motivation in the original design was that the Turntable should be intuitively to operate even if that meant that it was not optimally suited for all activity. The extra axis was hoped to remove the decomposition problem while continuing the simplicity of operation at the same.

In version 3 of the Turntable, shown in Figure 1-24, the roll axis was introduced to overcome the decomposition problem. The disk design, that separates the spin axis from the roll and the pitch axis, was continued. A button in the middle of the disk was introduced to provide a process known as “clutching” for the tilt and the roll axis. When the button is pressed output from the Turntable is ignored, the device can be now be oriented without influencing the object it is connected to. This is analogous to lifting the mouse when moving

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the cursor to a location out of reach. The introduction of the button eliminated both the limited tilt angle and the possible mismatch of the turntable and the object on the screen. Although its mechanical design was more sophisticated than that of its predecessors, version 3 was still based on cheap, off-the-shelve mouse components.

1.4.2 Evaluation of one-handed use of the Turntable

Turntable version 3 was evaluated for one-handed use before the evaluating it as part of a two-handed system. An experiment was conducted in which the Turntable was compared to a mouse-based orientation method. A detailed description of the experiment can be found in Gribnau, Verstijnen & Hennessey (1998). Here, the most important findings are summarized. The purpose of the experiment was to see whether a system with the Turntable used for the non-dominant hand would lead to efficient two-handed operation. The experiment described next verified the performance of the Turntable used with the non-dominant hand compared to that of the mouse used with the dominant hand.

The mouse cannot be used directly to specify orientations in 3D because it measures displacements in two directions while rotations about three axes are to be controlled. Several methods have been proposed in the past for this purpose. It was decided to use the method known as the virtual sphere (Chen, Mountford & Sellen 1988). This controller has been proven efficient for the task of specifying 3D orientations in research by Jacob and Oliver (1995). Figure 1-25 presents the screen of the experimental program. Subjects were asked to match the orientation of the object on the left with the orientation of the target object on the right several times with different target orientations. The experimental task

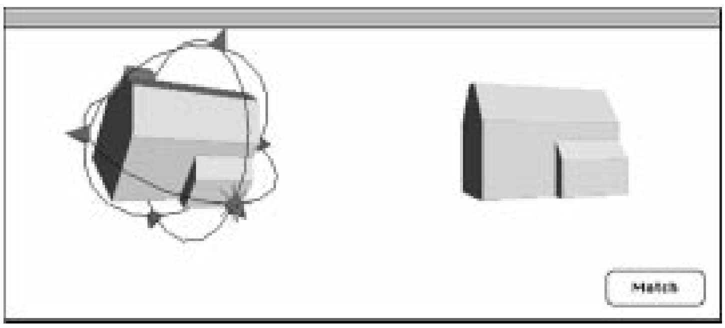


Figure 1-25. The screen of the experimental program. Subjects were asked to match the orientation of the object on the left with the orientation of the target object on the right.

resembled the task used by Chen et al. to compare different mouse operated orientation controllers. Both accuracy and completion time were dependent variables in the experiment. Subjects were asked to match the orientation of the identical objects as quickly and accurately as possible. A button in the lower right corner of the screen was pressed once the subject felt she or he had achieved an accurate match.

The test results showed that the performance of the Turntable, used with the non-dominant hand did not significantly differ from the performance of the virtual sphere operated with the mouse in the dominant hand. Regarding accuracy, it was found that mean angular errors were larger with the Turntable than with the virtual sphere but the results differed significantly only in the first half of the experiment. Later in the experiment, the difference in accuracy between Turntable and virtual sphere became statistically insignificant. The data also showed a problem of the Turntable not anticipated. In trials involving a lot of rotation about the roll axis (the axis not available in versions 1 and 2 of the Turntable), the Turntable performed worse than the virtual sphere. The design of the Turntable was believed to be responsible for this phenomenon. When the hand is placed upon the Turntable, the maximum angle of rotation about the roll axis is limited by the ergonomical limits of the wrist as presented by van der Vaart (1995). When the rotation of the hand is kept within these limits, most users can utilize approximately only half the roll range of the Turntable.

Overall, the Turntable proved to be capable of offering performance and accuracy comparable to the virtual sphere controller used with the mouse and the dominant hand. Although not tested in the experiment, the Turntable used with the non-dominant hand was expected to perform much better than the virtual sphere operated with a mouse in the non-dominant hand.

1.4.3 Evaluation of the Turntable used in a two-handed setup

The promising results of the performance of the Turntable led us to believe that two-handed operation with the Turntable device would be beneficial compared to one-handed operation. In a two-handed system, the Turntable can be used to orient an object while it is manipulated with the mouse at the same time. In a system with a mouse as the only interaction device, users have to constantly

switch between orienting the object and manipulation it with the mouse to accomplish the same functionality. A two-handed system could have performance benefits because of two reasons. First, two-handed operation can avoid the switching between orientation and manipulation mode and second, the temporal overlap of the actions performed by each hand could improve performance. The implicit assumption is that the Turntable when used with the non-dominant hand is easy to operate and well suited for orientation objects.
If this were not the case, the effect of the reduced switching could be voided because orienting with the mouse is faster than with the Turntable. If the Turntable were too difficult to operate, the effect of the temporal overlap could be canceled because concurrent operation would not exist. However, it was found that some aspects of the anticipated two-handed operation did not appear as expected after the creation of software to test this hypothesis. After a short description of the software, the problems encountered are described together with the reasons believed to have caused them.

The Turntable could not be used with standard CAD applications because it was specifically designed as the non-dominant hand device in a two-handed system. Most CAD applications support interaction with one device at a time, commonly the mouse. Moreover, most operating systems of desktop computers do not support the concurrent use of multiple interaction devices and therefore most applications are not equipped for handling concurrent input streams either. If input from more than one device is accepted, the devices can usually only be operated sequentially, controlling the same functionality. For true two-handed operation, the application needs to accept input from two devices simultaneously and the two input streams should be mapped to two different components of the same combined activity. Therefore, an application was needed to test the viability of two-handed interaction with the Turntable and the mouse.
It was decided to evaluate two-handed input with an editing task resembling the functionality of household and workshop tools mentioned before. One hand is used to orient an object with the Turntable while the other hand moves points on the surface of the object with the mouse. Figure 1-26 shows how the Turntable can control the orientation of the cube in the center of the screen.
To the user, it appears as if the cube is placed on the Turntable because it follows the Turntable's rotations. In Figure 1-27, it is

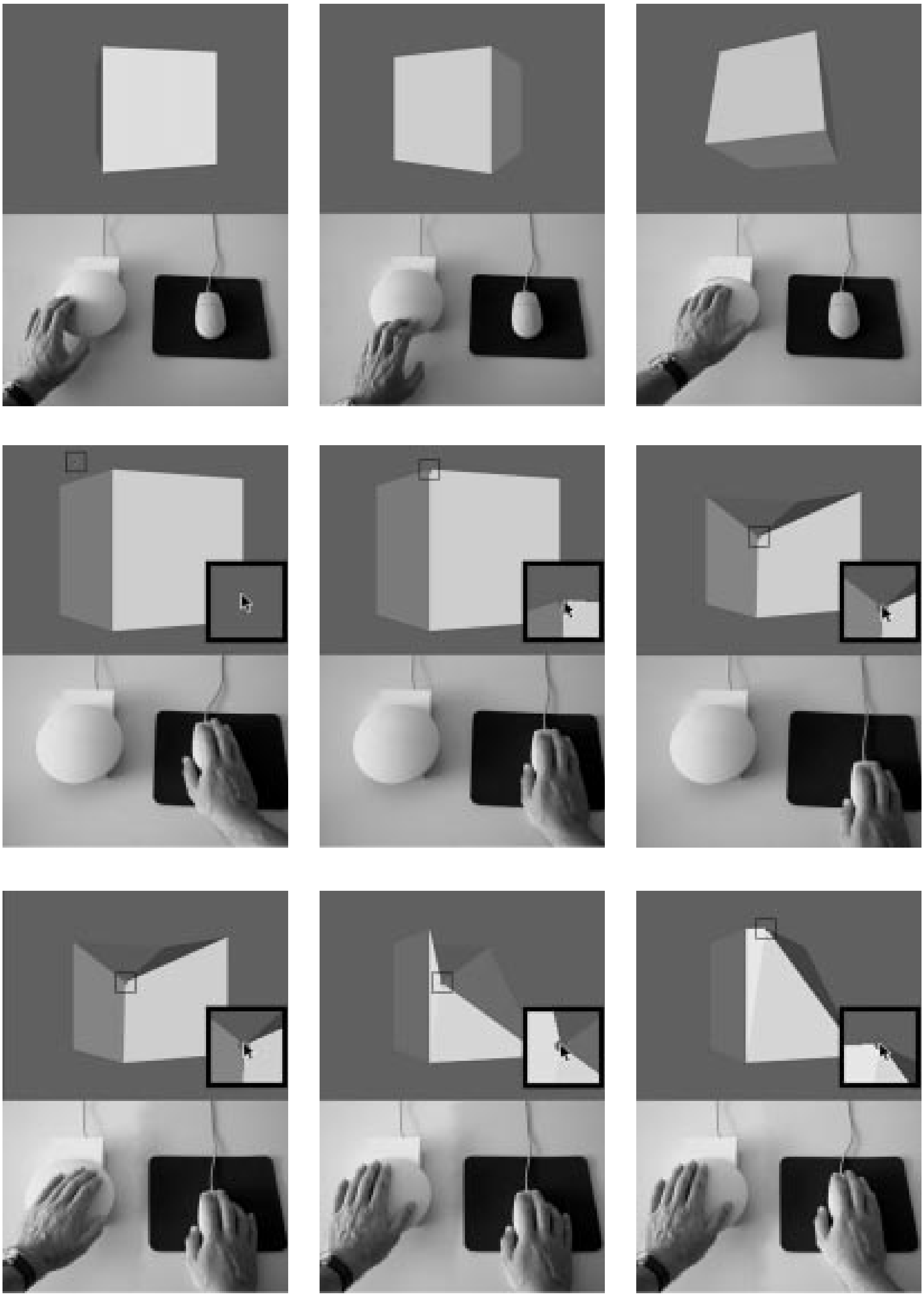
shown how the mouse can be used to select vertices on the surface of the cube. As soon as the cursor is located in front of a vertex, a red dot appears at the location of the vertex. The vertex can subsequently be moved by dragging with the mouse. Shown in Figure 1-28 is how both operations, orienting the cube with the Turntable and moving vertices with the mouse, can occur simultaneously.

Preliminary testing with the test application confirmed the conclusions of earlier testing with the Turntable and the Grabber. Users commented that operating the Turntable was easy and intuitive and dragging vertices was straightforward too as expected. However, when users were asked to modify the shape of the cube, the expected concurrent operation of two hands produced surprising results that interfered with the task. Moreover, users found it difficult to complete a simple task in a short time, such as transforming the cube into another shape like a pyramid, even with sequential use of the devices.

The use of the mouse for dragging vertices was believed to be the main reason for this. While the Turntable orients the object in 3D directly, users had to control the position of the vertices with a 2D mouse. The result was that vertices could only be moved in a plane parallel to the screen. To position a vertex in an arbitrary location, the user had to perform a sequence of movements in different views of the object. This problem is also found in many CAD applications and commonly addressed by presenting three orthogonal views to the user. To position entities, the user operates the mouse in several views successively. Therefore, the user has to decompose the intended 3D movement of a vertex into successive 2D movements with the mouse. This cumbersome procedure is similar to the decomposition of rotational degrees of freedom, encountered above.

The decomposition problem is believed to prevent two-handed operation in two ways. First, positioning a vertex in 3D is so involving that all the attention of the user is directed towards accomplishing this activity. The additional control of the Turntable with the other hand would introduce yet another amount of cognitive load.

The other reason is that the combination of rotation of an object with the Turntable and movement of a vertex on the object with the



mouse may lead to unpredictable results. This can be seen when concurrent dragging of a vertex and orientation of the object is considered. All the vertices in the neighborhood of the moved vertex will be displaced towards or away from the user because of a Turntable rotation. Nevertheless, the vertex controlled with the mouse stays at the same distance from the user. This makes it difficult for users to predict the outcome of a concurrent operation with both hands. It is for example impossible to move an object and a vertex on its surface at the same time while keeping the vertex at the same location on the surface in a single combined two-handed gesture.

Figure 1-26. Rotating a cube with the Turntable.

It was concluded that the Turntable did indeed perform well for rotating objects but the combined use of Turntable and 2D interaction devices such as the mouse was problematic. Furthermore, the 2D display did influence the predictability of the outcome of the user's actions. The use of the Turntable in two-handed operation as such was not denied. Instead, it was believed that the main obstacle for fast and intuitive two-handed manipulation could be attributed to the 2D interaction device.

1.5 Conclusion

Above, the need for computer-supported conceptual modeling was discussed. In addition, it was found that conventional CAD systems exhibit problems that prevent them from being used for conceptual modeling. Next, the goals of the research were formulated, motivated by the discrepancy between the needs of conceptual modeling and the quality of the tools available. The Turntable research and the review of experimental CAD systems have shown that the use of two-handed operation and alternative interaction devices has the potential to enhance computer-supported modeling. This inspired the formulation of the original research goal:

Figure 1-27. Moving a vertex with the mouse.

> *Improve computer support of conceptual modeling.*

However, this goal was too comprehensive to cover in this work and therefore, a more specific goal was formulated:

> *Establish how two-handed interaction in 3D can improve computer support of conceptual modeling.*

Figure 1-28. Moving a vertex and rotating the cube at the same time.

Both 3D and two-handed interaction are considered means to provide the designer with a more efficient, expressive way of

operating a computer system which is more akin to his normal hand skills. These characteristics, when applied in a modeling system, will preferably allow the designer to explore different strategies and focus on the creative task at hand instead of the distraction of operating the CAD system. However, this optimistic view is yet to be established and could be countered by arguing that operating the computer with two hands and controlling many degrees of freedom is more difficult than working with most current CAD systems. Nevertheless, it is expected that working with two hands in 3D is a more natural situation for modeling with the computer and allows the designer an explorative manner, thereby facilitating conceptual modeling. Consequently, when a CAD system with this kind of interaction fails to deliver a more efficient and expressive level of operation, something has gone wrong in the way the two-handed operation and 3D interaction have been implemented.
Both two-handed operation and 3D interaction have not found acceptance in mainstream CAD systems. Moreover, most current computer interfaces lack support for either two-handed operation or 3D interaction that have mostly been employed in some experimental systems. The consequence is that little is known on how to optimally apply these interaction concepts either separately or in combination. Therefore, many questions are expected to arise during the research needed to create successful tools for conceptual 3D modeling.

It was realized that two-handed operation and 3D interaction are not the only possibilities for improving conceptual modeling with a computer because there are alternative means of input (e.g. speech input). Apart from that, the input media are just a part of the total interaction between a user and the computer system. The output media are an essential part of the cycle too. As shown above, certain output technologies can display objects directly in 3D as opposed to 2D display on a computer screen. This can improve the interaction with a CAD system because the designer is better informed about the shape of a model. However, to narrow the scope of the research enough to make it feasible within the timeframe of a Ph.D. project, it was decided to focus on two-handed interaction in 3D primarily.

In summary, this work is embedded between two issues. The first issue deals with the question of how to create a good CAD system for conceptual modeling. The second issue is the question of how to apply two-handed operation and 3D interaction for this purpose.

The answer to the latter question is expected to be more generally applicable than for a CAD system alone. It is anticipated that both two-handed and 3D interaction are useful in other application areas too. Some other application areas have been encountered in of experimental systems, such as medical and architectural research. In addition, the many-DoF (Degree of Freedom) input could become important in the face of the currently emerging complex electronic worlds. For example, three-dimensional worlds are increasingly used for communication and visualization purposes. Technologies such as VRML (Virtual Reality Markup Language) provide the means to distribute 3D worlds over the Internet. Furthermore, it is possible for users to interact with these worlds and with other users present in the same world. The potential of these technologies is becoming even more apparent now that an average consumer computer is capable of displaying 3D worlds interactively. However, the methods of interacting with these worlds are generally limited by interaction techniques. The result is that 3D worlds can be conveyed well but interaction with those worlds is restrained.

1.6 The structure of the research

"Plan de campagne"

Having established the goal of the research, the approach for realizing the goal is described. In short, the approach consisted of an explorative phase, an investigative phase, a constructive phase and an evaluative phase. In the investigative phase, research in the field of computer human interaction was reviewed, followed by the constructive phase during which a system was created that allows prototyping interaction devices and interaction techniques. In the evaluation phase, several interaction techniques were evaluated. The arrangement of the remaining chapters reflects the approach of the research. In the following description of the phases of the research, the related chapters are indicated.

1.6.1 Explorative phase

The Turntable research was the explorative phase of the research. It has been presented in this chapter and it helped identify and refine the research goals. In applying the Turntable, it was encountered that two-handed operation is not easily incorporated

in current CAD systems because of two reasons.
First, because effective two-handed operation of a computer system involves more than adding an extra device to the system. Secondly, because current CAD systems do not provide the means to connect an extra device for supporting two-handed operation. Both reasons indicated the need for an investigation about the nature of concurrent two-handed operation and the way it should be implemented in computer systems.
The Turntable research also pointed to the use of alternative interaction devices as a means to enhance the interaction between computer and designer. One of the problems of using 2D interaction devices for modeling is that a 3D model is being manipulated. The discrepancy between manipulation in 2D and the 3D task introduces a barrier between the designer and the design. This motivated the study of the potential of 3D interaction as a means to provide the designer with a more direct relationship with the design during development.

1.6.2 Investigative phase

In the investigative phase, a survey of the state of the research in computer human interaction was conducted, with emphasis on aspects relevant to the goal of conceptual modeling. The research described in this work builds upon a body of research from different fields. In general, research in the field of computer human interaction relates to a number of different disciplines and this research is no exception. It borrows from fields like psychology, computer science, ergonomics, graphic design, electrical and mechanical engineering (Jacob, Leggett, Myers & Pausch, 1993).
The next chapter presents the results of the investigative phase and it embeds this research within the other research in the field of computer human interaction. The purpose of the chapter is to present the fundamentals for the creation of a tool for the evaluation of interaction techniques for conceptual modeling.
Classifications of interaction devices from literature will be presented to help discriminate interaction devices and to find the characteristics of devices suited for conceptual modeling. With the majority of current interaction techniques, it is assumed that operation takes place with a 2D interaction device, such as the mouse. Since this assumption does not apply in this project where alternative interaction devices were investigated, the current interaction techniques are also reconsidered for other interaction

devices. In addition, two-handed operation does have implications for interaction techniques. Therefore, literature about two-handed operation will be presented and examples of computer systems with two-handed interaction are given.

1.6.3 Constructive phase

In the constructive phase, a system was built with which interaction devices and interaction techniques could be prototyped and evaluated. The system was necessary because no system existed that allowed for prototyping two-handed interaction techniques, let alone a system that offered support for heterogeneous interaction devices which was needed to determine the suitability of these devices for tasks. Thus, the system needed to be built from the ground up. Several rounds of design and preliminary testing were performed before a significant amount of functionality was considered successfully implemented and ready for evaluation.
Another aspect of the constructive phase was the development of an interaction device, which is called the Frog. The development was motivated by the fact that there were almost no 3D interaction devices available at that time. A handheld device was needed that sensed 6-DoF, meaning that it outputs both its position and orientation in three dimensions. The development of the Frog was based on research by Zhai, Milgram and Buxton (1996) and Hinkley, Pausch, Goble and Kassell (1994b) among others. It is an ergonomically formed cover for a 6-DoF sensor. It allows for a two-button input and it is shaped specifically for the purpose of precision input.
Chapter 3 describes the design and implementation of the ID8Model[5] system that supports both two-handed operation and a range of interaction devices. ID8Model is used as a test-bed for the evaluation of interaction devices and interaction techniques.
The design of the system allows for dynamic assignment of interaction devices to different functionality in the program.
It currently provides a number of modeling tools such as the generation of primitives, assembly, scaling, drawing and various shape modification tools.

1.6.4 Evaluation phase

In the evaluation phase, the system was used to evaluate several aspects of the two-handed interaction techniques that were developed. The evaluation with user tests took place in two stages. In the first stage, two experiments were conducted in which two-

[5] “ID8” is an acronym for “IDEATE”.

handed operation was compared to one-handed operation. Conceptual modeling in general comprises a lot of functionality, not all of which could be tested in the experiment. Therefore, it was decided to use one task, namely the assembly or putting together of objects. The assembly task was believed to be representative for a range of modeling tasks in a modeling system. The purpose of the experiment was to locate the benefits of two-handed operation in the context of computer assisted modeling. It is found that two-handed interaction has benefits regarding performance and workload but not for all tasks.
This part of the evaluation phase is presented in Chapter 4. The chapter describes the two experiments that employed the same assembly task. The first experiment suggested that two-handed operation led to faster completion times. However, the experimental design complicated the interpretation of the results for completion times. Therefore, the second experiment was carried out to verify the results of the first experiment. Regarding workload it was found that with two-handed operation, the workload was balanced between both hands and the total workload was not increased compared to one-handed operation.

In the second stage of the evaluation, another experiment was conducted. In this experiment, several two-handed interaction techniques were compared. The same assembly task was used to test an alternative for the two-handed interface of the previous experiments. The alternative interface is more generally applicable for other tasks (e.g. shape creation and modification) than the assembly task alone. The alternative interface also allowed the testing of another aspect of 3D interaction relating to user comfort. A common notion about 3D interaction is that it must be fatiguing for users to work with their hands in the air. This is true as long as there is not a clutch mechanism (Hinkley, Pausch, Goble & Kassell, 1994a) that allows users to remain in a comfortable posture while interacting with the system. In the experiment, two clutch mechanisms were tested and the implications for the user were evaluated.
Chapter 5 presents the results of the experiments in the second stage of the evaluation. The hypothesis was that the alternative interface was more demanding to operate for users but that was proven false after the experiment. With the alternative interface, users achieved comparable performance and workload. Combined

with the fact that the alternative interface is more generally applicable, it has become the interface of choice. The conclusion of the comparison of the clutch mechanisms was that they were not of significant influence to performance and workload but that they reduce fatigue. They also encouraged different task solution strategies.

In Chapter 6, the general conclusions can be found. It will be verified that the research has contributed to both the fields of computer interaction and industrial design. In fact, over the course of this project, these fields became increasingly overlapping since industrial designers themselves are getting involved in interaction design issues for clients.