The Interactive Creation of 3D Objects Using Deformations - A User Based Study of Physical and Geometrical Paradigms

Kou, Shancy

The Interactive Creation of 3D Objects Using Deformations - A User Based Study of Physical and Geometrical Paradigms

by

Shancy Kou

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Em memoria ao meu irmao Jacques
e ao meu tio Orlando.
In memory to my brother Jacques
and my uncle Orlando.

Abstract

This thesis is concerned with the interactive creation and manipulation of 3D objects in computer graphics and in particular with the creation and manipulation of the shape of such objects by deformations. Two paradigms, physical and geometrical, can be employed to effect such deformations in shape and a comparison of these two methods provides the main focus of this thesis.

The fundamental working hypothesis of this research was that physical deformations would bring a significant increase in efficiency and user satisfaction in the creation and manipulation of solid objects when compared with geometrical deformations. This hypothesis was based on the notion that when employing physically based deformations users would be able to call on existing knowledge of such processes from everyday life.

A user based empirical study was carried out including a pilot study involving twenty subjects followed by the main study with forty subjects. The main subjects were all undergraduate students and were divided into two groups, one reading Arts and the other reading Sciences.

In order to test the major hypothesis two versions of an application were constructed, one based on the simulation of deformations through the application of physical laws and the other based on purely geometric constraints. Using these two applications a comparison between these paradigms could be made. However, assurance was needed that the developed user interface would not by itself affect the comparison between the paradigms. Therefore, as a first stage, the newly developed geometrical representation was compared against two other existing commercial geometrical applications in order to test the developed interface. Once the new interface was tested, showing that it was indeed preferred and performed better than the other two, the comparison of the paradigms was carried out.

The study comparing the physical and geometrical methods showed that, in general, physically based deformation systems did not significantly improve efficiency or user satisfaction in comparison with models based on geometric constraints only. Nevertheless the study also provided data for a more in-depth analysis where a class of user has been identified for which the physically based model may be more appropriate.

Therefore the main contribution of this thesis is the description and analysis of the results of a user based study which concluded that the use of physical deformations in the creation of solid objects offers no real significant benefit when compared against the geometrical deformation. Thus the simulation of physical laws becomes irrelevant and the computational expense of implementing these laws not worthwhile when set against geometrical methods, in the context of interactive object creation and manipulation.

These findings may prove useful for designers choosing paradigms for applications involving interactive 3D modelling using deformations.

Acknowledgments

I consider all the people with whom I have had or still have a friendship during the course of this research to be invaluable. They all supported me at different stages and without all of them I would not have finished.

As I cannot possibly name them all I want to express my honest gratitude to you all for being there when I needed you.

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This thesis reports on work which would have never being possible if I had not had the highest of standards of supervision provided by Mel Slater. He has taught me many things, some in relation to the work I was doing and others on a more personal level, like how to deal with the problems facing me when I was under pressure. Thank you.

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Chapter 1 Introduction

1.1 Introduction

There has being a growing interest in the scientific community in developing "physical" models in order to replicate the physical attributes of reality. Some examples are physical models that simulate gravity and air-resistance [1], heat and melting [63], elasticity [60], viscoelasticity, plasticity and fracture [62] and many more. Among these there are also systems which simulate physical laws to be used for creating graphical 3D objects [11,60,65].

These systems however are very computationally expensive due to the complexity of implementation of these physical laws. This can be a problem particularly for the interactive creation and manipulation of 3D objects which is already a time consuming and tedious process.

This work therefore started with the purpose of examining a simplified physical approach to simulating physical laws in respect to the creation and manipulation of 3D objects.

The idea was to develop a deformable 3D object which would behave like a "lump of clay".

While considering such a model however, it was felt that even a simplified approach would still require quite a lot of processing power. Geometrical models which simulate deformations [7,8,17,23], although not based on physical laws, can be much less computationally expensive and produce impressive results. Thus what might be the advantages of a physical model? That it might be more intuitive and more easily understood than a geometrical one? If this is the case then, is there a real gain in execution and learning time by "replicating" reality? If so, is it significant? Are tasks executed faster because the user already has previous real world knowledge to apply when executing the tasks? Is the user more satisfied with the task performed if his/her previous knowledge was used?

These questions are fundamental and guided this research. They form the basis of main concern of this thesis in the area of creation and manipulation of 3D graphical objects: "Does a physical approach to deformations bring a significant increase in efficiency and user satisfaction when compared to a geometrical approach?".

This work attempts to answer this question and contributes to knowledge about a comparison of these two paradigms, physical and geometrical.

The terms 'deformation', 'physical', 'geometrical' and 'user interface' need to be firstly defined in the context of this work. This is considered in the next section and will be followed by the aims and objectives of this thesis, describing in more detail the main issue of comparing the two approaches including how they were evaluated. Next the scope is presented, defining the limits and constraints with which the work was carried out. This is followed by the presentation of the findings which resulted from the evaluation of the methods. Finally, a brief description of the following chapters shows the reader the way in which this thesis is organized.

1.2 Definition of Terms

The term 'deformation' in the context of this research relates to the manipulation of an existing 3D graphical object in order to create a new one [52], that is, to reshape it. Moreover this 3D graphical object is geometrically represented, for example as polyhedra in a suitable data structure, or an ordered set of vertices.

The term 'geometrical' is associated with a deformation constrained only by the geometric model employed in the representation of the 3D object. For example, the geometrical definition of B-Spline surfaces [21] establishes geometrical constraints in relation to its control points. Thus when deforming such a surface by manipulating its control vertices those constraints are enforced.

On the other hand the 'physical' term is associated with a deformation constrained by the geometric model employed *plus* a set of constraints based on physical laws. For example, physical constraints, such as elasticity and plasticity, are added to the geometrical constraints. The deformation model then reacts to the application of forces at a particular point or a set of points on its surface based on the physical properties of the material and it responds accordingly.

The term 'user interface', frequently used when stating that "the two methods were developed with the same user interface", refers, in this thesis, to the style of interaction, presentation of data and feedback of the applications. Of course, strictly speaking the methods cannot have the 'same' user interface because they have different functionality, but this term will be adopted as notation for presentation and interaction style.

1.3 Aims and Objectives

The main concern of this thesis is an investigation into the use of physical against geometrical deformations in the creation and manipulation of 3D graphical objects. In particular this research focuses on determining whether there is a significant improvement in user execution time of tasks when physical deformations are used and, if the user is more satisfied with the end result of a task when it involves previous knowledge about behaviour of objects in the physical world.

In order to answer such questions an investigation was carried out which compared the two methods, physical against geometrical. However, if applications that had different user interfaces were compared, any findings from the comparison, could have being due to the difference in functionality or to the difference in user interface. Hence this work provided implementations of the two methods with the same user interface so to minimise its influence in the comparison between the methods.

Nonetheless one can still argue that the proposed interface might not be of an acceptable standard and may still affect the comparison between the methods. Therefore in order to eliminate this possibility two analyses were carried out. The first analysis compared the developed application using the geometrical method against existing commercial geometrical applications. This served to evaluate the standard of the proposed user interface. The second analysis then used the same results from the developed geometrical application against the developed physical application. This served to evaluate both methods.

In addition, users have knowledge about the physical world, the objects in it and how they behave. Technically oriented users might perform differently from arts oriented users. Therefore in order to examine this possibility two groups of subjects were used and a hypothesis proposed that one group would be more suitable for a particular task than the other. In this case one group was formed by students reading Arts and the other by students reading Sciences. Furthermore, since this study was concerned with 3D objects, a spatial ability test was carried out in order to check the possibility that spatial ability would be differently distributed amongst Arts and Sciences based students. This test served also to examine the effects of spatial ability on task performance.

1.4 Scope

The objects used in this research were represented as polyhedra. Therefore the developed application and others, which were used for comparison purposes, were capable of supporting this class of objects.

All the applications used for this research supported the following features:

- direct manipulation of objects;
- concave and convex objects;
- viewing of an object according to a general camera model, where the centre of projection, viewplane and view up vector can be specified interactively;
- translating, rotating and scaling of objects;
- grouping or linking of objects;
- duplicating and deleting objects;
- at least one method for deformation.

The version of the application which embodied the physical method provided, in addition, a cutting function for objects and the simulation of pull and push reactions applied to an object. However these pull and push reactions were partial simulations of physical laws in that this simulation used the internal mass stress in an object instead of a true representation, and therefore did not take into account all the elasticity and plasticity properties. This was because the purpose of the simulation was to test if users would be positively influenced by the physical approach or not and to evaluate the extent of interaction.

Data for the response of users to both types of paradigm and user interface were gathered from an experimental study. Two samples were used, one from a population of students reading Arts, that is languages and human geography, and the other from a population of students reading Sciences, that is, medicine, chemistry, biology, astrophysics and engineering. Data to test the hypothesis that Arts students would have a different degree of spatial ability than Sciences students came from a spatial ability test [45] and a visual/ auditory/kinaesthetic questionnaire [54,55].

The experimental studies included timings, questionnaires and observations before, during and after the execution of six tasks. These tasks involved the creation of solid 3D graphical objects based on real clay models shown to subjects. The six objects were: a primitive (such as a tetrahedron), a primitive with a cut (such as a tetrahedron without two corners), an abstract (such as a pyramid with two spikes), an object made by revolution, that is, an object with rotational symmetry (such as a bottle), a composite (such as a chair) and a general object (such as an aeroplane).

Furthermore novice computer users were targeted in an attempt to reduce the effect of previous computer knowledge on performance.

1.5 Contributions

The main contributions of this thesis are

- the description and the analysis of the results of a large user study comparing the physical and geometrical paradigms for the creation of 3D graphical objects. This includes comparisons of performance amongst Arts and Sciences based users.

Other contributions include:

- a survey of existing physical and geometrical methods of deformation;
- the implementation of two methods of deformation, physical and geometrical;
- the development of a common user interface for the methods implemented;
- the elaboration of a graphics tutorial for computer novices;
- the definition of a methodology which uses real clay models, a spatial ability test, introduction sheet, a tutorial, questionnaires and an observation sheet for the evaluation of user interfaces and deformation methods;
- the identification of characteristics which define suitable users for each of the methods;
- the identification of user characteristics related to each application.

1.6 Organization of this Thesis

The next chapter presents a description and discussion (where appropriate) of existing physical and geometrical methods of deformations.

Chapter 3 describes the method used in this thesis for the simulation of physical deformations, its derivation and its implementation.

Chapter 4 presents objects, operations and user interface for the two versions of the application built by this work plus the other two geometrical applications used for the interface analysis.

Chapter 5 describes the evaluation process, the design of tasks, questionnaires and other elements used during the user based experiments, ending with a description of how the experiments were conducted.

Chapter 6 presents the results of the analyses which include the spatial ability analysis, user interface analysis and physical against geometrical analysis. These are followed by a discussion about the findings and a summary.

Chapter 7 presents a summary of this thesis, a list of the main contributions and proposes future work.

Chapter 2 Deformation Methods

2.1 Introduction

This chapter presents a survey of available techniques, their description and a discussion of each method (where appropriate). The chosen geometrical method is presented; the physical approach is then introduced, and its implementation is described in Chapter 3.

2.2 Sculpting

In essence the purpose of deformation is to reshape an existing object. Mathematically speaking, solid 3D objects are represented by point sets in 3D Euclidean space. Such solids are formed by boundary points plus inside points, for example, in the case of an unit sphere we have

$$\{ (x\ ,y,z) \mid (x^2+y^2+z^2) \leq 1 \} \tag{1}$$

However, this kind of representation in an abstract 3D space needs to be converted to a representation within a computer environment. To do so, the 3D Euclidean space is transformed to a 3D coordinate system in a computer. The way we see such a system depends on the kind of display we are using, that is, if it is a 2D display the 3D coordinate is projected into the 2D display and each cell in the display is called a *pixel*. On the other hand, if the display is 3D then the 3D coordinate is projected into the 3D display coordinate system and each of its cell is called a *voxel*.

So, a simple way to reshape such an object would be to add or delete voxels from it. Such an idea was implemented by Galyean and Hughes [23] who introduced the notion of **Sculpting** a solid material. This technique is similar to the concept of "paint" programs where bitmap values are changed according to the state of a "brush", i.e. '1' to denote paint and '0' to denote empty. In this case the solid material is represented as a set of voxel data later transformed (for rendering purposes) into a polygonal surface using the "marching cube" algorithm [39]. As in "paint" programs, tools, such as "sandpaper" and "heat-gun", are provided. However, the term "sculpting" is more appropriate considering that the user starts with a pre-defined shape (like a cube) and works his/her way to produce the desired object. Although simple, this method requires large storage space and computational cost for every voxel, making it suitable for parallel processing techniques.

A quicker way to work with 3D objects in a sequential architecture would be to use a mathematical representation where far less data is required and changes to the objects would be processed much faster.

Such a way is to represent 3D solid objects through their boundary representation, that is, just the set of boundary points represent the object. For example, in the case of a sphere, we have

$$\{ (x, y, z) \mid (x^2 + y^2 + z^2) = 1 \} \tag{2}$$

Such a set of points, which would represent the boundary, can also be voxels [18].

So, as voxels in solid objects, boundary regions can be moved freely to deform objects.

2.3 Transformations

Either solid or boundary representations can be used to deform an object by applying transformations to it. From the set of basic transformations (rotation, scaling and translation), the scaling matrix on its own already provides a form of deformation. However these transformations could be combined to create a new set. Such ideas were developed by Barr [8] who introduced a new set of operations which include tapering, axial twist and linear bend. Tapering is achieved by changing the length of two global components without changing the length of the third. For example, a tapering along the z axis is

$$\begin{aligned} X &= rx \\ Y &= ry \\ Z &= z \end{aligned} \tag{3}$$

where $r = f(z)$.

Just as tapering is a differential scaling, axial twist is a differential rotation where one pair of global basis vectors is rotated as a function of height while the third one remains unchanged. The analogy given is twisting a deck of cards where each card is rotated somewhat more than the card beneath. Thus, a twist around the z axis is given by

$$\begin{aligned} X &= x\cos\theta - y\sin\theta \\ Y &= x\sin\theta + y\cos\theta \\ Z &= z \end{aligned} \tag{4}$$

where $\theta = f(z)$.

Completing the set, the linear bend operation first needs the definition of the basis vector, i.e. along which axis the bend will occur (say Y). A bent region is then defined (y_{min}, y_{max}) where the differential basis vectors are simultaneously rotated and translated around the third basis vector. However, outside the bent region the deformation consists of a rigid body rotation and translation. Thus a linear bend along the Y axis is given by

$$X = x$$

$$Y = \begin{cases} -\sin\theta\left(z-\frac{1}{k}\right)+y_0, & y_{min} \le y \le y_{max} \\ -\sin\theta\left(z-\frac{1}{k}\right)+y_0+\cos\theta\,(y-y_{min}), & y < y_{min} \\ -\sin\theta\left(z-\frac{1}{k}\right)+y_0+\cos\theta\,(y-y_{max}), & y > y_{max} \end{cases} \tag{5}$$

$$Z = \begin{cases} \cos\theta\left(z-\frac{1}{k}\right)+\frac{1}{k}, & y_{min} \le y \le y_{max} \\ \cos\theta\left(z-\frac{1}{k}\right)+\frac{1}{k}+\sin\theta\,(y-y_{min}), & y < y_{min} \\ \cos\theta\left(z-\frac{1}{k}\right)+\frac{1}{k}+\sin\theta\,(y-y_{max}), & y > y_{max} \end{cases}$$

where θ is the bending angle and is given by

$$\theta = k\left(\hat{y}-y_0\right) \tag{6}$$

where k is the constant bending rate, measured in radians per unit length, and where

$$\hat{y} = \begin{cases} y_{min}, & y \le y_{min} \\ y, & y_{min} < y < y_{max} \\ y_{max}, & y \ge y_{max} \end{cases} \tag{7}$$

Although processing time of these transformations and the representation of data is much faster compared to voxel data, the appearance of a local deformation is achieved only by applying a transformation to the whole object or by dividing the object into patches and applying the transformation to the desired ones.

2.4 Curves

As transformations can be combined to create new ones, existing trigonometric functions can be changed to create new primitives. **Superquadric solids** [7], which are based on the spherical product of pairs of curves, do just that by raising trigonometric functions to a power.

For example if the spherical product is solved with two sine-cosine curves, with their trigonometric functions raised to a power (say ε) as in Eq (8).

$$\underline{x}(\phi, \theta) = \begin{bmatrix} \cos\phi^{\varepsilon_1} \\ a_3 \sin\phi^{\varepsilon_1} \end{bmatrix} \otimes \begin{bmatrix} a_1 \cos\theta^{\varepsilon_2} \\ a_2 \sin\theta^{\varepsilon_2} \end{bmatrix} \qquad (8)$$

The result is

$$\underline{x}(\phi, \theta) = \begin{bmatrix} a_1 \cos\phi^{\varepsilon_1} \cos\theta^{\varepsilon_2} \\ a_2 \cos\phi^{\varepsilon_1} \sin\theta^{\varepsilon_2} \\ a_3 \sin\phi^{\varepsilon_1} \end{bmatrix}, -\pi/2 \le \phi \le \pi/2, -\pi \le \theta \le \pi \qquad (9)$$

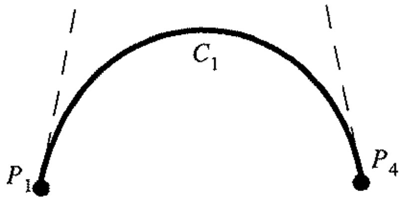
which is called a superellipsoid. ε_1 is the 'squareness' parameter which controls the shape of the solid in the north-south direction and ε_2 is the squareness parameter which controls the shape in the east-west direction. Certain parameter values give shape characteristics:

$$\begin{array}{l} \varepsilon < 1 \Rightarrow \text{shape is somewhat square} \\ \varepsilon \sim 1 \Rightarrow \text{shape is round} \\ \varepsilon \sim 2 \Rightarrow \text{shape has a flat bevel} \\ \varepsilon > 2 \Rightarrow \text{shape is pinched} \end{array} \qquad (10)$$

Although superquadric solids can have their shape changed by changing their squareness parameters, such changes are still symmetric round the related axis (north-south or east-west), that is, if a power is changed it will affect the object equally on both sides of the axis.

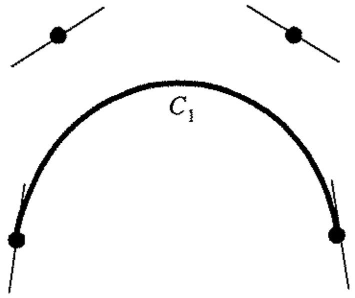
Another way to form a boundary representation of an object is by creating a surface made by a number of parametric curves [21,22]. Curves are defined by a number of control points, for example in Figure 1 P_1, P_2, P_3, P_4 define the Bezier [21] curve C_1.

Figure 1 - Curve control points



Control points can have weights attached to them, that is, the 'heavier' the control point the more the curve will be attracted towards it. Another way to control a curve is to change the direction of control point tangent vectors (Figure 2).

Figure 2 - Control point tangent vectors

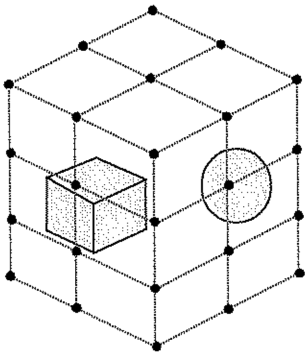


Different kinds of curves, for example Hermite, Bezier or splines [21], use different combinations of these elements. Different curves form different surfaces so in order to deform such a surface one manipulates its degree, control points, weights or tangent vectors. Such manipulation is rather simple when dealing with simple objects but it becomes more and more difficult as the object gets more complex. The number of control points needed in the definition of the object becomes very large making it difficult for the user to control them. In particular the clutter doesn't allow the user to have a clear control of the necessary changes s/he wants to make. Moreover these surfaces are approximated rather than interpolated, that is, although the surface is governed by the control points the same surface does not pass through these control points (Figure 1). Therefore the manipulation of the surface's shape becomes very difficult since the user needs to interact with points which do not lie in the surface itself although are closely related to it.

There are interpolating solutions for B-Splines surfaces which can be interactively modified [36] but the problem of clutter of shape control points still remains.

One way to reduce the number of control points when deforming an object is by using curves just as a guide in the deformation, as shown by Sedeberg and Parry [51] in their method known as **Free-Form Deformation (FFD).** The FFD method uses Bernstein polynomials [21] to generate a frame that covers an object or a group of objects to be deformed (Figure 3). The deformation is then carried out by moving the control points of the polynomials in the frame, which in turn controls the deformation of the objects contained within.

Figure 3 - FFD frame with undisplaced control points

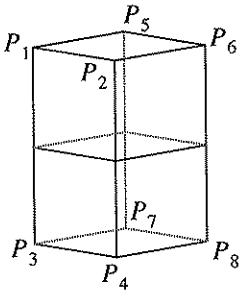


Moreover an extra degree of freedom can be added to the deformation tool by incorporating weights into each control point. Since this is done by including rational basis functions in the formulation of the deformation this method became known as **Rational Free-Form Deformation (RFFD)** [33].

FFDs and RFFDs enclose the whole object and are therefore very suitable for global deformations. Local deformations can be achieved by wrapping just part of the object to be deformed with a lattice. This lattice then can be deformed, changing the shape of the part of the object which it covers while the rest of the object which is not covered by the lattice remains the same. This however introduces continuity problems.

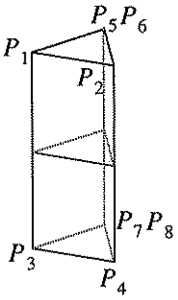
One solution for basic continuity in local deformations is to use two or more lattices in a single object. This idea was implemented in the **Extended Free-Form Deformation (EFFD)** [17] method which starts by transforming the parallelepipedical lattice (Figure 4) used in FFD and RFFD into a prismatic one (Figure 5).

Figure 4 - Parallelepipedical lattice



According to the author of the method all prismatic lattices obtained by moving or merging any points of a parallelepipedical lattice are valid. As an example a prismatic lattice (Figure 5) can be obtained by merging the two top and the two bottom vertices of a parallelepipedical's face (Figure 4). In this case, for simplicity, just the corner vertices are numbered. So P_5 and P_6, P_7 and P_8 from Figure 4 were merged to form the prismatic lattice of Figure 5.

Figure 5 - Prismatic lattice



These prismatic and parallelepipedical elements can then be welded together to form more complex lattices which support more local deformations than FFD and RFDD can offer. Still one problem remains, in order to achieve a desired local deformation one needs first to weld the elements in such a way as to form a lattice, which will provide the local control desired. This is rather a difficult task from the user's point of view.

FFD, RFFD and EFFD, however, do not support the direct manipulation of the objects but of the lattice covering the object. Up to now changes have been made to the control points in the lattice and these passed to the object. These process however can be reverted, that is, changes made in the object can be passed to the control points. This idea is presented in the **Direct Manipulation of Free-Form Deformations (DFFD)** [31]. DFFD allows the user to choose one or more point(s) in the object and move it(them) to a desired position. Constraints are then used to adjust the positions of the control points forming the lattice.

However, once again local deformations can be a problem. The size, position and boundary of the deformation are directly linked to the lattice, that is, its size, number and position of control points. Therefore to achieve a local deformation the user might need to make changes to the surrounding lattice which defies the purpose of the method.

Curves can also guide the deformation of a surface as presented by Welch and Witkin [70] in their **Variational Surface Modelling**. A sum of tensor-product B-splines [21] is used to represent a surface and points and curves are attached to it forming geometric constraints. The user then can deform the surface by manipulating these points or curves. Any number of points and curves can be attached to the surface in any position or direction making the method rather flexible. But this freedom to place the constraints in any direction might work against the user when deforming complex objects since, as with the number of control points in curve surfaces, there might be a clutter of necessary constraints making the interaction rather difficult.

Another way in which curves are used to guide a deformation was presented by Chang and Rockwood [13] whereby an object is deformed by wrapping it along a user defined Bezier curve. This wrapping is achieved by applying affine transformations in space to the object using a **Generalization of the de Casteljau Algorithm** [21].

A user specifies a Bezier curve [21] where at each control polygon the user also specifies a pair of handles which are used as a local coordinate system for the transformations. The object is then mapped along the defined Bezier curve by iterative affine transformations derived from the handles and control polygons.

Figure 6 - Wrapping an Object along a User Defined Bezier Curve

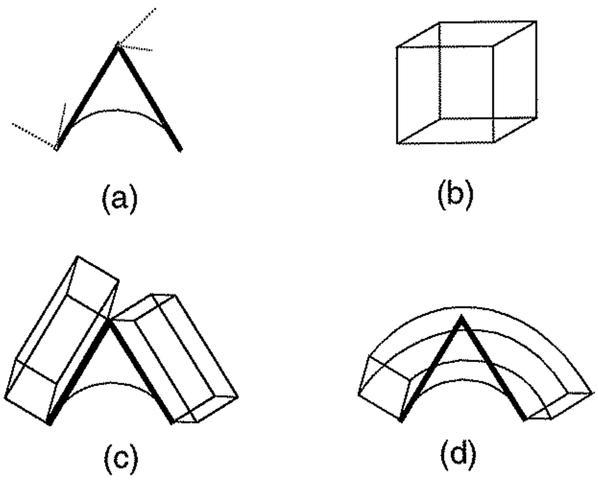


Figure 6 shows an example with (a) a user defined curve with control polygons and handles at one end point of each control polygon, (b) a cube to be deformed, (c) the cube mapped to each segment of the control polygon and finally (d) the cube mapped along the Bezier curve.

This wrapping method can mimic the tapering, twisting and bending operations developed by Barr [8] and described on page 23 but likewise it allows just symmetric deformations around the defined Bezier curve. That is, in the example given on Figure 6, both sides of the cube wrapped along the curve were deformed, one cannot deform just one of its side leaving the other intact. Moreover for complex objects a great number of control polygons and handles would need to be defined so to give it more local control.

2.5 Physical Equations

Apart from the geometrically based methods described, another alternative to achieve deformations is the use of physical phenomena or physical laws.

The above geometrical methods, although ways of deforming objects, do not have any relation to real world reactions when deformations occur. Physical equations can be applied to a 3D object representation in order to get deformations which can be associated with real world reaction. Such realism relies on people's intuition of how deformations work in real life.

Physical laws are incorporated into geometrical models to simulate a variety of 'real' actions such as contact, collision and/or friction [4,5,6,24,34,43], motion [5,12,16,29,46,66], gravity and air-resistance [1], heat and melting [63], elasticity [60], viscoelasticity, plasticity and fracture [62]. Other simulations deal with a whole physical system such as simulating hair [2], waves and surf [49], muscle [12,15,33,64], skin deformations [24,28,64] or clothes [10,47,67]. Such simulations are applied to rigid and/or deformable bodies [40]. The work in this thesis, however, is concerned with deformations, therefore attention will be given only to simulations using deformable bodies.

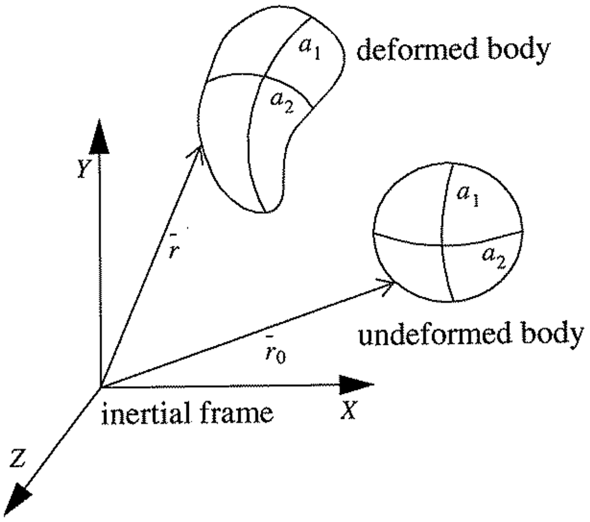
Starting from a more primitive shape we have particle systems. A particle system consists of a large number of point masses (particles) moving under the influence of external forces such as vortex fields, collisions with stationary obstacles and Newton's Laws of motion. In the absence of external forces and constraints, 3D particle systems tend to arrange themselves into solids rather than surfaces. For this reason Szeliski and Tonnesen [59] introduced the **Oriented Particle System** in which each particle represents a small surface element (with its own local coordinate) with added orientation, i.e. a normal vector and a local tangent plane to the surface (defined by the local x and y vectors). Such particles can then be displaced and the whole object can be rendered by a rendering technique such as triangular meshing, discs, crosses or a more complex shading algorithm (for example Phong).

However, as voxel data, particles don't have any geometrical relation to each other so more computation is required to simulate their dynamics. Since some level of real-time user interaction is required, parallel processing is needed.

An example of geometrically represented deformable model, which uses physical laws is the primary evaluation of an elastic model by Terzopoulos at al [60].

An inertial frame is positioned in the geometric space and the deformed position calculated in relation to this inertial frame as shown in Figure 7.

Figure 7 - Primary Model



In order to have a deformation calculated, differential equations of motion are used to describe the dynamic behaviour of a deformable model under the influence of external forces. Such equations can be expressed in Lagrange's form as follows:

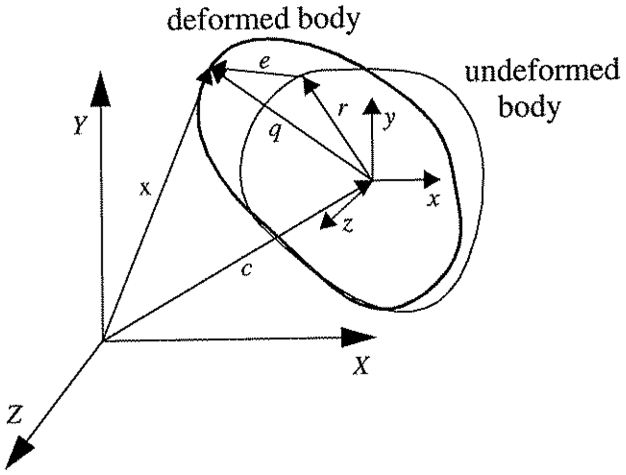
$$\mu\frac{\partial^2 \underline{r}}{\partial t^2} + \gamma\frac{\partial \underline{r}}{\partial t} + \delta_r\varepsilon = \underline{f}(a, t) \qquad (11)$$

where $\underline{r}(a, t)$ is the position of the particle a at time t, $\mu(a)$ is the mass density of the body at a, $\gamma(a)$ is the damping density, $\delta_r\varepsilon$ is the internal elastic force which resists deformation and $\underline{f}(a, t)$ represents the net externally applied forces. The first term is the inertial force due to the model's distributed mass. The second term is the damping force due to dissipation and the third term is the elastic force due to the deformation of the model away from its natural shape.

Although the above method simulates certain aspects of a physical environment, it is only concerned with perfect elastic deformations. Real materials, however, are not perfectly elastic all the time, they might have different reactions such as a certain amount of restore or different behaviour depending on the history of applied forces. Some different reactions, that is, viscoelasticity, plasticity and fracture, were added by Terzopoulos and Fleischer [61,62] in their hybrid deformable model.

The hybrid evaluation, as opposed to the primary, is related directly with the initial state of the body. The model's new position is the result of the composition (q) of two vectors, r from the origin of a noninertial frame located at the undeformed body's centre of mass and e from the undeformed to the deformed position as show in Figure 8.

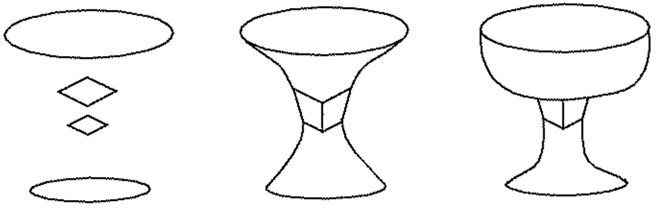
Figure 8 - Hybrid Model



The hybrid method can be applied to the Superquadric solids described in page 24 to form **Deformable Superquadrics** [65]. These primary and hybrid evaluations simulate elasticity and plasticity to a high standard but as with the majority of physical systems they can be very expensive in terms of processing power.

Another way to use physical laws to deform objects would be to apply them to geometric primitive equations in order to create new ones which would have deformable properties. Celniker and Gossard [11] developed this idea and introduced two deformable primitives: a deformable curve and a deformable surface. They used these primitives to introduce the **"Shape Wright" Paradigm** which is intended for the design of free-form shapes. An object is created in three phases (Figure 9): a) a set of 3D character lines, that is, deformable curve segments, define the object; b) the object is skinned where over every face a deformable surface is created and c) the object is then sculpted by interactively applying forces and loads which will change its original shape.

Figure 9 - The Shape Wright Paradigm



a) character lines b) skinned c) sculpted

The deformable curve and surface are governed by an energy functional which takes the general form

$$E_{deformation} = \int_{\sigma} (\alpha \text{ stretch} + \beta \text{ bending}) \, d\sigma \qquad (12)$$

This energy function is subjected to geometric constraints that a user loads in order to build a shape which naturally attempts to resist stretching and bending. Thus in order to deform a surface the user needs to apply point, slope and edge geometric constraints, define loads and modify α and β values, which are not necessarily intuitive. All these necessary definitions might make interaction not at all straight forward.

Vassiliev [68] extended the deformable surface presented by Celniker and Gossard by developing a new energy functional with an extra term (γ hardness) which controls the hardness of the surface. This extra parameter gives more control over a surface but also adds to the number of parameters which need to be specified in order to control a deformation making the interaction process potentially more laborious.

These methods again can be very expensive for large objects.

2.6 Conclusions

Existing methods to simulate deformations were presented and may be broadly divided into two groups: geometrically and physically based. The geometrically based methods use just geometrical constraints of a geometrical representation of an object in order to control a deformation. The physically based methods use the geometrical and physical constraints based on physical laws.

This research proposes to implement a representation of each method in order to draw a suitable comparison.

On the geometrical side one needs to take into account that the chosen method will be implemented and compared against other existing applications. So, although more elaborate methods were reviewed here, the implementation of the simpler method of freely moving vertices of an object's boundary representation was chosen since is more widely available for comparison.

On the physical side however, for the reasons given after each method description (mainly speed of processing and level of user interaction), a simpler method which still gives 'realism' and is directly interactive could be used. Such a method, a simplification of the Finite Element Method (FEM), was chosen for this work and its description and implementation are described in the next chapter.

Chapter 3 Finite Element Method (FEM)

3.1 Introduction

This research focus on a small number of operations to do with deformation: cut, join, pull and push.

Cut and join are two operations which will be implemented separately and will be described in the next chapter. Pull and push can be forces applied to vertices of an object so deforming it. An underlying relationship that relates the forces applied to the resulting displacements needs to be modelled. Thus, this chapter proposes the use of the Finite Element Method (FEM) [38,41,50,71] which determines the relationship between the forces and displacements in terms of object's stiffness.

First the notation used throughout this chapter will be presented followed by the method itself.

The method starts with its definition, together with the concepts used followed by the definition of an element (in this case a tetrahedron) and continues with the method's derivation (4 steps), the assembly of elements, application of constraints and finally the overall calculation of displacements.

3.2 Notation

In the following, a node is defined as a vertex which belongs to an element (tetrahedron).

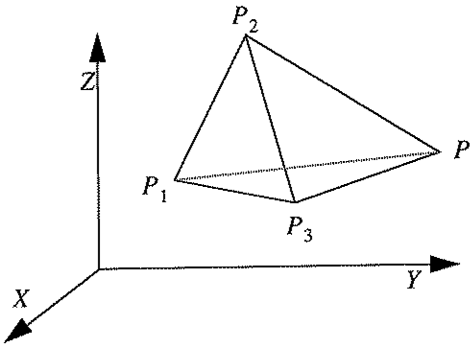
$[A]$	coefficient matrix associated with displacement
$[B]$	matrix relating element strains to element nodal displacements
$[D]$	elasticity matrix
E	Young's modulus
F	force
$\{F\}$	vector of nodal forces
F_x, F_y, F_z	forces in x, y, z directions
$[K]$	stiffness matrix
u, v, w	displacements along x, y, z axes
x, y, z	rectangular Cartesian co-ordinate system
α_1, α_2	constants used in displacement function

δ	displacement
$\{\delta\}$	vector of nodal displacements
ε	strain
$\varepsilon_x, \varepsilon_y, \varepsilon_z$	direct strains
σ	stress
$\sigma_x, \sigma_y, \sigma_z$	direct stresses
ν	Poisson's ratio
$[\ ]$	indicates a matrix
$\{\ \}$	indicates a one-dimensional array, row or column vector
$[\ ^e], \{\ ^e\}$	matrix, vector relating to a single element
$[\ ]^T$	transpose of matrix
$\{\ _i\}, x_i$	indicates quantities associated with node i
(x, y, z)	indicates quantities are functions of x, y, z
$[\ ]^{-1}$	inverse of matrix

3.3 General Definitions for an Element (tetrahedron)

Consider a tetrahedron formed by P_1, P_2, P_3, P_4 in the space defined by the X, Y, Z co-ordinate axes as shown in Figure 10, where $P_i = (x_i, y_i, z_i)$, $i = 1, 2, 3, 4$ and each P_i 'sees' the $P_j (j \neq i)$ in a anti-clockwise order.

Figure 10 - Tetrahedron



The displacement at, say P_1, $\{\delta_1\}$ is defined by three displacement components, u in the X direction, v in the Y direction and w in the Z direction forming the displacement vector (u, v, w).

Using matrix notation, the displacement vector at P_1 may be written as

$$\{\delta_1\} = \begin{bmatrix} u_1 \\ v_1 \\ w_1 \end{bmatrix} \tag{13}$$

Likewise, the corresponding force vector at P_1 may be written as

$$\{F_1\} = \begin{bmatrix} F_{x1} \\ F_{y1} \\ F_{z1} \end{bmatrix} \tag{14}$$

The complete displacement and force vectors for the element (tetrahedron) may be written as

$$\{\delta^e\} = \begin{bmatrix} \{\delta_1\} \\ \{\delta_2\} \\ \{\delta_3\} \\ \{\delta_4\} \end{bmatrix} = \begin{bmatrix} u_1 \\ v_1 \\ w_1 \\ u_2 \\ v_2 \\ w_2 \\ u_3 \\ v_3 \\ w_3 \\ u_4 \\ v_4 \\ w_4 \end{bmatrix} \tag{15}$$

$$\{F^e\} = \begin{bmatrix} \{F_1\} \\ \{F_2\} \\ \{F_3\} \\ \{F_4\} \end{bmatrix} = \begin{bmatrix} F_{x1} \\ F_{y1} \\ F_{z1} \\ F_{x2} \\ F_{y2} \\ F_{z2} \\ F_{x3} \\ F_{y3} \\ F_{z3} \\ F_{x4} \\ F_{y4} \\ F_{z4} \end{bmatrix} \tag{16}$$

3.4 The Method

A 3D solid object is, as its name implies, solid, that is, not just a boundary but it actually has a volume. Thus this object can be 'broken' into smaller solid pieces, which can be called 'elements' of the original object. These elements in turn can be assembled back in the right places, like a jig-saw puzzle, to form the original object.

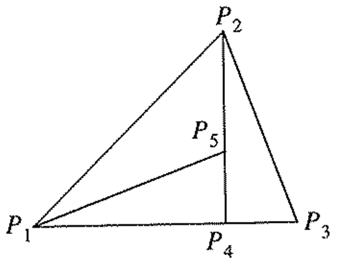
This principle of dividing an object (or structure) into smaller elements, performing some calculations and then re-assembling them to give an overall result for the whole object is the basis of the Finite Element Method (FEM) [38,41,50,71].

FEM is used in engineering to calculate the balance of forces and displacements in complex structures. The method is called 'finite' because it involves subdividing the structure into finite elements and using the calculation obtained at each element to form an overall result for the whole structure.

An element, in computer graphics terms, is a polyhedra which needs to be versatile enough to produce the most complex objects. For this reason, the smallest polyhedron, the tetrahedron, was chosen as the primitive for the elements.

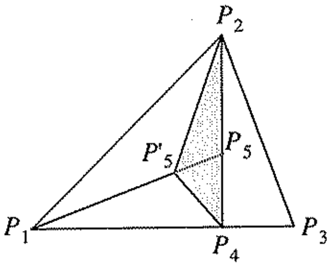
Several techniques for the subdivision of triangular elements into smaller triangular elements exist [9,19] and these can be modified to suit the subdivision of tetrahedrons. This subdivision is carried out on an element to element basis and therefore needs to be robust enough so to avoid "t-vertices" (Figure 11). Depending on the criteria used to stop the subdivision and as the initial elements differ in size, there may be a case (Figure 11) where a shared edge is subdivided for one element but not for the other one which shares it.

Figure 11 - T-vertex



If this occurs and in the process of deformation P_5 is moved, a gap will form in the structure (Figure 12).

Figure 12 - Gap in the structure caused by movement of t-vertex



Another issue which the subdivision method needs to deal with has to do with mesh distribution. Ideally a mesh needs to be evenly distributed, that is, the elements that form the mesh should be as similar as possible in size and shape.

In order to avoid both problems, t-vertices and poor mesh distribution, two methods were combined resulting in the following procedure: find the tetrahedron's longest edge and if longest edge is longer than a threshold then subdivide the tetrahedron into 2 smaller tetrahedra. This subdivision is achieved by connecting the longest edge to the opposite vertex.

Splitting the tetrahedron in half produces a good distribution and the threshold for the longest edge guarantees that no t-vertices are formed.

So, once the structure is divided into finite elements and the applied forces are known, a relationship needs to be found relating the applied forces to the unknown displacements. The FEM method employs a 'stiffness' analysis in order to define this relationship. The stiffness analysis relates the applied nodal forces $\{F\}$, or forces applied to vertices of elements, to the unknown displacements $\{\delta\}$, that is

$$\{F\} = [K]\{\delta\} \tag{17}$$

where the quantity $[K]$ is the 'stiffness' of the complete structure.

However in order to solve this system of equations for the whole structure, we need to assemble the results from each individual element within the structure.

From Eq (17) we can say that the relationship between the force vector in an element (tetrahedron) $\{F^e\}$ and the displacement vector $\{\delta^e\}$ is given by

$$\{F^e\} = [K^e]\{\delta^e\} \tag{18}$$

where $[K^e]$ is the element stiffness matrix.

Now, considering we know $\{F^e\}$, to calculate the unknown displacements $\{\delta^e\}$ we need first to calculate $[K^e]$.

The next sections therefore describe how $[K^e]$ can be derived and how all the elements can be assembled to form the overall stiffness matrix for the structure. Once the overall matrix is assembled, the systems of equations can be solved to find the unknown displacements.

The element stiffness matrix $[K^e]$ can be derived in 4 steps: relate general displacements within an element to its nodal displacements, relate strain to displacement, relate stress to strain and replace stress with nodal forces. Each of these steps are described below in detail. These are followed by the assembly of all the elements to form the overall matrix $[K]$ from Eq (17) which represents the whole structure. Finally the definition of some constraints and the calculation of the overall displacements are presented.

3.4.1 Displacement at any point

The state of displacement δ of a point is defined by three displacement components, u, v, w in the directions of the three co-ordinates X, Y, Z. Using matrix notation, the displacement vector at any point may be written as

$$\{\delta(x, y, z)\} = \begin{bmatrix} u \\ v \\ w \end{bmatrix} \qquad (19)$$

Since there are twelve degrees of freedom, twelve unknown coefficients $(\alpha_1, \alpha_2, \ldots, \alpha_{12})$ are required when representing the permitted displacement pattern in polynomial form. The simplest representation is given by the three lines

$$\begin{aligned} u &= \alpha_1 + \alpha_2 x + \alpha_3 y + \alpha_4 z \\ v &= \alpha_5 + \alpha_6 x + \alpha_7 y + \alpha_8 z \\ w &= \alpha_9 + \alpha_{10} x + \alpha_{11} y + \alpha_{12} z \end{aligned} \qquad (20)$$

which can be written in matrix form as

$$\{\delta(x,y,z)\} = \begin{bmatrix} 1 & x & y & z & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & x & y & z & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & x & y & z \end{bmatrix} \begin{bmatrix} \alpha_1 \\ \alpha_2 \\ \alpha_3 \\ \alpha_4 \\ \alpha_5 \\ \alpha_6 \\ \alpha_7 \\ \alpha_8 \\ \alpha_9 \\ \alpha_{10} \\ \alpha_{11} \\ \alpha_{12} \end{bmatrix} \tag{21}$$

or more concisely as

$$\{\delta(x,y,z)\} = [f(x,y,z)]\{\alpha\} \tag{22}$$

Now if we substitute the values of the nodal co-ordinates into Eq (22) we have the combined displacement for the element:

$$\{\delta^e\} = \begin{bmatrix} \{\delta_1\} \\ \{\delta_2\} \\ \{\delta_3\} \\ \{\delta_4\} \end{bmatrix} = \begin{bmatrix} \{\delta(x_1,y_1,z_1)\} \\ \{\delta(x_2,y_2,z_2)\} \\ \{\delta(x_3,y_3,z_3)\} \\ \{\delta(x_4,y_4,z_4)\} \end{bmatrix} = \begin{bmatrix} [f(x_1,y_1,z_1)] \\ [f(x_2,y_2,z_2)] \\ [f(x_3,y_3,z_3)] \\ [f(x_4,y_4,z_4)] \end{bmatrix} \{\alpha\} \tag{23}$$

which may be written as

$$\{\delta^e\} = [A]\{\alpha\} \tag{24}$$

It should be noted that all the terms in matrix $[A]$ are known since they simply consist of the co-ordinates of the element nodes.

The unknown polynomial coefficients $\{\alpha\}$ are now determined from Eq (24) by inverting the matrix of coefficients $[A]$ to yield

$$\{\alpha\} = [A]^{-1}\{\delta^e\} \tag{25}$$

By using Eq (22) the displacements $\{\delta(x,y,z)\}$ at any point (x_i, y_i, z_i) within the element can now be determined in terms of the nodal displacements $\{\delta^e\}$. Hence if we substitute $\{\alpha\}$ from Eq (25) into Eq (22) we get

$$\{\delta(x,y,z)\} = [f(x,y,z)][A]^{-1}\{\delta^e\} \tag{26}$$

3.4.2 Strain relation to nodal displacement

Six strain components form the strain vector $\{\varepsilon(x, y, z)\}$ [71] which is given as follows

$$\{\varepsilon(x,y,z)\} = \begin{bmatrix} \varepsilon_x \\ \varepsilon_y \\ \varepsilon_z \\ \varepsilon_{xy} \\ \varepsilon_{yz} \\ \varepsilon_{zx} \end{bmatrix} = \begin{bmatrix} \frac{\partial u}{\partial x} \\ \frac{\partial v}{\partial y} \\ \frac{\partial w}{\partial z} \\ \frac{\partial u}{\partial y} + \frac{\partial v}{\partial x} \\ \frac{\partial v}{\partial z} + \frac{\partial w}{\partial y} \\ \frac{\partial w}{\partial x} + \frac{\partial u}{\partial z} \end{bmatrix} \tag{27}$$

Substituting u, v, w from Eq (20), solving the partial derivatives and isolating $\{\alpha\}$ we have

$$\{\varepsilon(x,y,z)\} = \begin{bmatrix} 0&1&0&0&0&0&0&0&0&0&0&0 \\ 0&0&0&0&0&0&1&0&0&0&0&0 \\ 0&0&0&0&0&0&0&0&0&0&0&1 \\ 0&0&1&0&0&1&0&0&0&0&0&0 \\ 0&0&0&0&0&0&0&1&0&0&1&0 \\ 0&0&0&1&0&0&0&0&0&1&0&0 \end{bmatrix} \begin{bmatrix} \alpha_1 \\ \alpha_2 \\ \alpha_3 \\ \alpha_4 \\ \alpha_5 \\ \alpha_6 \\ \alpha_7 \\ \alpha_8 \\ \alpha_9 \\ \alpha_{10} \\ \alpha_{11} \\ \alpha_{12} \end{bmatrix} \tag{28}$$

or simply

$$\{\varepsilon(x,y,z)\} = [C]\{\alpha\} \tag{29}$$

Substituting $[A]^{-1}\{\delta^e\}$ for $\{\alpha\}$ from Eq (25) we have [50]

$$\{\varepsilon(x,y,z)\} = [C][A]^{-1}\{\delta^e\} \tag{30}$$

which may be written as

$$\{\varepsilon(x,y,z)\} = [B]\{\delta^e\} \tag{31}$$

3.4.3 Internal stress related to strain

The relationship between the internal stress $\{\sigma(x, y, z)\}$ and strain $\{\varepsilon(x, y, z)\}$ can be expressed as

$$\{\sigma(x, y, z)\} = [D]\{\varepsilon(x, y, z)\} \tag{32}$$

Substituting $\{\varepsilon(x, y, z)\}$ from Eq (31) we get

$$\{\sigma(x, y, z)\} = [D][B]\{\delta^e\} \tag{33}$$

where $[D]$ in terms of the usual elastic constants E (modulus) and ν (Poisson's ratio) is given in [41]

$$[D] = \begin{bmatrix} d_{11} & d_{12} & d_{13} & 0 & 0 & 0 \\ d_{21} & d_{22} & d_{23} & 0 & 0 & 0 \\ d_{31} & d_{32} & d_{33} & 0 & 0 & 0 \\ 0 & 0 & 0 & d_{44} & 0 & 0 \\ 0 & 0 & 0 & 0 & d_{55} & 0 \\ 0 & 0 & 0 & 0 & 0 & d_{66} \end{bmatrix} \tag{34}$$

which is symmetric and where

$$\begin{aligned} d_{11} &= d_{22} = d_{33} = \frac{E(1-\nu)}{(1+\nu)(1-2\nu)} \\ d_{21} &= d_{12} = d_{13} = d_{31} = d_{23} = d_{32} = \frac{E\nu}{(1+\nu)(1-2\nu)} \\ d_{44} &= d_{55} = d_{66} = \frac{E}{2(1+\nu)} \end{aligned} \tag{35}$$

3.4.4 Internal stresses related to statically equivalent nodal forces

Now that we have a relationship between the displacement, stress and strain, the principle of virtual work is used to relate these to statically equivalent nodal forces hence finding the element stiffness matrix $[K^e]$ of Eq (17).

Virtual work [38,41,50,71] means that during any displacement imposed on the element, the total external work done by the nodal loads must be equal to the total internal work done by the stresses.

So if we consider δ' to be the imposed displacement, the external work (W_{ext}) done by the nodal loads is given by [50]

$$W_{ext} = \{\delta_1'\}\{F_1\} + \{\delta_2'\}\{F_2\} + \{\delta_3'\}\{F_3\} + \{\delta_4'\}\{F_4\} = \{\delta^{e\prime}\}^T\{F^e\} \tag{36}$$

whereas if the imposed displacement causes strains ($\{\varepsilon'(x, y, z)\}$) at a point within the element where the actual stresses are $\{\sigma(x, y, z)\}$, then the internal work done per unit volume is given by

$$W_{int} = \{\varepsilon'(x, y, z)\}^T \{\sigma(x, y, z)\} \tag{37}$$

and the total internal work is obtained by integrating over the volume of the element, hence

$$\int^v W_{int} d(vol) = \int^v \{\varepsilon'(x, y, z)\}^T \{\sigma(x, y, z)\} d(vol) \tag{38}$$

Now from Eq (31) we can write the strains corresponding to the imposed displacement as

$$\{\varepsilon'(x, y, z)\} = [B] \{\delta^{e'}\} \tag{39}$$

Furthermore, from Eq (33) the actual stresses in the element are known to be related to the actual nodal displacements as

$$\{\sigma(x, y, z)\} = [D] [B] \{\delta^e\} \tag{40}$$

Therefore, if we substitute Eq (39) and Eq (40) into Eq (38) we have the internal work as

$$\int^v W_{int} d(vol) = \int^v [B]^T \{\delta^{e'}\}^T [D] [B] \{\delta^e\} d(vol) \tag{41}$$

Now that we have the internal and external work defined we can equate them to represent the work done during the system of virtual displacement $\delta^{e'}$ to yield

$$\{F^e\} = \left[\int^v [B]^T [D] [B] d(vol)\right] \{\delta^e\} \tag{42}$$

On comparing to Eq (18) which states that

$$\{F^e\} = [K^e] \{\delta^e\} \tag{43}$$

we find that the required element stiffness matrix $[K^e]$ is given by

$$[K^e] = \int^v [B]^T [D] [B] d(vol) \tag{44}$$

However, since the matrices $[B]$ and $[D]$ contain only constants and considering that the volume is also constant we can simplify the above equation to get

$$[K^e] = [B]^T [D] [B] V \tag{45}$$

where V represents the volume of the elementary tetrahedron.

Now if we solve $[B]$ from Eq (31), which is a simplification of Eq (30), we have

$$B = \begin{bmatrix} b_1 & 0 & 0 & b_2 & 0 & 0 & b_3 & 0 & 0 & b_4 & 0 & 0 \\ 0 & c_1 & 0 & 0 & c_2 & 0 & 0 & c_3 & 0 & 0 & c_4 & 0 \\ 0 & 0 & d_1 & 0 & 0 & d_2 & 0 & 0 & d_3 & 0 & 0 & d_4 \\ c_1 & b_1 & 0 & c_2 & b_2 & 0 & c_3 & b_3 & 0 & c_4 & b_4 & 0 \\ 0 & d_1 & c_1 & 0 & d_2 & c_2 & 0 & d_3 & c_3 & 0 & d_4 & c_4 \\ d_1 & 0 & b_1 & d_2 & 0 & b_2 & d_3 & 0 & b_3 & d_4 & 0 & b_4 \end{bmatrix} \tag{46}$$

where

$$b_1 = -\det\begin{bmatrix} 1 & y_2 & z_2 \\ 1 & y_3 & z_3 \\ 1 & y_4 & z_4 \end{bmatrix} \tag{47}$$

$$c_1 = \det\begin{bmatrix} x_2 & 1 & z_2 \\ x_3 & 1 & z_3 \\ x_4 & 1 & z_4 \end{bmatrix} \tag{48}$$

$$d_1 = -\det\begin{bmatrix} x_2 & y_2 & 1 \\ x_3 & y_3 & 1 \\ x_4 & y_4 & 1 \end{bmatrix} \tag{49}$$

and from Eq (34) we have $[D]$ as

$$D = \frac{E(1-\nu)}{(1+\nu)(1-2\nu)}\begin{bmatrix} 1 & & & & & \\ \frac{\nu}{(1-\nu)} & 1 & & & & \\ \frac{\nu}{(1-\nu)} & \frac{\nu}{(1-\nu)} & 1 & & & \\ 0 & 0 & 0 & \frac{(1-2\nu)}{2(1-\nu)} & & \\ 0 & 0 & 0 & 0 & \frac{(1-2\nu)}{2(1-\nu)} & \\ 0 & 0 & 0 & 0 & 0 & \frac{(1-2\nu)}{2(1-\nu)} \end{bmatrix} \tag{50}$$

where E (modulus) is the elastic constant and ν Poisson's ratio [38].

Therefore now we can calculate $[K^e]$ from Eq (45) which results in a 12 x 12 symmetric matrix. where each triplet row and column is related to each vertex's degrees of freedom

(x, y, z) , that is, rows and columns 1, 2 and 3 are related to P_1 , rows and columns 4, 5 and 6 are related to P_2 and so on

3.4.5 Assembling the Overall Stiffness Matrix

Once all the individual stiffness matrices for each tetrahedral element are calculated, then they are assembled into an overall stiffness matrix that represents the whole object (Eq (17)).

The whole structure of the elements is implemented as a list of faces which points to a list of vertices which are uniquely numbered. A vertex's number identify the position of its related rows and columns in the overall stiffness matrix, i.e., P_1 related columns would start at column 1 in the overall matrix whereas say P_{10} related columns would start at column 28. The same rule is applied to the related rows.

However, if the vertices are not in increasing order, e.g. (P_1, P_2, P_4, P_3) , then the rows and columns relating to P_4 need to be swapped with the rows and columns relating to P_3 , i.e. columns 7, 8 and 9 are first swapped by 10, 11 and 12 then rows 7, 8 and 9 are swapped by 10, 11 and 12 before putting them into the overall matrix.

3.4.6 Applying Boundary Conditions

Once the overall stiffness matrix is assembled the boundary conditions, i.e. constraints of no displacement, must be applied. These constraints are represented by a number of fixed vertices where at least two need to be specified. Once specified, the boundary condition is applied by eliminating the related rows and columns of the respective fixed vertices chosen from the overall stiffness matrix. Such elimination is done by setting all the elements in the related rows and columns to zero and setting the diagonal element (intersection between the eliminated row and column) to one.

3.4.7 Calculating the Overall Displacement

Now that the forces are defined, the overall stiffness matrix is assembled and the boundary conditions are applied, the systems of Eq (17) can be solved to determine the displacement at each vertex.

Considering that the overall matrix is symmetric, a specialized Gaussian elimination method, known as LDL^T decomposition [27] is used to solve the system of equations.

If we consider a system of equations where $Ax = b$, the method computes a unit lower triangular matrix L and a diagonal matrix D such that $A = LDL^T$. Once the LDL^T decomposition is obtained, the solution to $Ax = b$ may be found by solving the following three systems:

$$\begin{aligned} Ly &= b \\ Dz &= y \\ L^T x &= z \end{aligned} \tag{51}$$

3.5 Summary

This chapter presented the Finite Element Method (FEM) used to simulate physical deformations. It described the method, the definition of an element, the method's derivation, its constraints and the assembly of the elements in order to calculate the overall displacement.

This method used the internal stress of an object as a way to simulate a certain degree of elasticity. It was implemented in one version of the application developed by this work whereas the other version employed translation of vertices as a way of representing the geometrical deformation. These two versions then could be evaluated. However, before this could be done, other geometrical applications needed to be chosen in order to take part in the first analysis which involved the evaluation of the user interface.

These applications together with the developed one are presented in the next chapter along with the description of their objects and operations and user interface.

Chapter 4 Objects and Operations and User Interface

4.1 Introduction

Now that the method used for the simulation of physical deformations has been presented, this chapter will concentrate on the applications used for the investigation into its use.

A discussion of the available applications and the choices made will be presented. This will be followed by a description of objects, operations and user interface for each of the applications used (including the ones developed by this work) so that the reader gains the necessary information to understand the user based investigation described in the next chapter.

4.2 Available applications

As described in Chapter 1 the applications needed to support the following features:

- polyhedral representation of solid objects;
- direct manipulation of objects;
- concave and convex objects;
- viewing of an object according to a general camera model, where the centre of projection, viewplane and view up vector can be specified interactively;
- move, rotate and scale of object;
- grouping or linking of objects;
- duplicate and delete objects;
- at least one method for deformation.

In addition to these there were other factors which needed to be taken into account when selecting which application to use.

Since this investigation concentrates on computer novices the applications needed to have a user interface which could be presented to a novice in a short space of time (not more than one hour) and where its objects and operations could be easily understood and assimilated.

Three applications used for the construction of 3D objects were considered: AUTOCAD [3], Swivel3D Professional [58] and Interactive 3D Modeler (I3DM) [32]. The latter is a demonstration application which comes with the Silicon Graphics Indigo machines whereas the others are commercial ones.

AUTOCAD is a very popular technical graphical application used mainly by engineers and architects. It's definition and manipulation of objects can be done through menus, command lines or direct access menus. Newer versions allow the direct manipulation of objects. It has a single camera view where the objects are created and manipulated.

Swivel3D Professional works in two modes: one for the creation and reshaping of objects and the other for their manipulation. The creation and reshaping of objects work on the principle of architectural or engineering drawings, where an object is seen as a set of three plans: cross-section, side-section and top-section. The manipulation of objects is viewed through a single camera. The user interface uses icons and menus.

The Interactive 3D Modeler (I3DM) allows the creation and manipulation of objects through menus, command line and a set of four views: front, right, top and perspective.

These applications support all the necessary requirements, therefore, the factors related to the learning process on the account of computer novices are decisive.

AUTOCAD presents the user with many ways of doing an operation (menus, command lines and direct menus). It also presents the user with a great number of operations which are beyond the scope of this investigation. These many ways and many operations might cause confusion and screen clutter which might in turn cause some degree of fear for novices. Thus AUTOCAD was discarded as a possible application used for comparison.

Swivel3D and I3DM on the other hand present the user with fewer ways and fewer operations therefore they were included in this investigation.

The other two applications used, Interactive Modeller (IM) and Interactive Deformable Modeller (IDM) were the applications built by the author for this work. IM used the geometrical method of deformation whereas IDM used the physical method.

4.3 Basic Objects and Operations

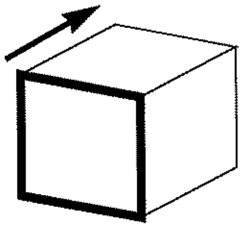
There are a number of objects and operations which are common to all applications, which have to be defined before objects and operations and user interface for each of the applications are presented.

The lowest level of abstraction in this case is called an *outline* which can then be used to form an *object*. However, these must exist in what is called a *World*. Outlines can be *extruded* or *rotated* to form 3D objects.

Extruding it means to push the outline of an object back a certain distance so to form a solid.

For example, to create a cube by extrusion the outline (represented by the thicker lines) would be:

Figure 13 - Cube's outline for extrusion

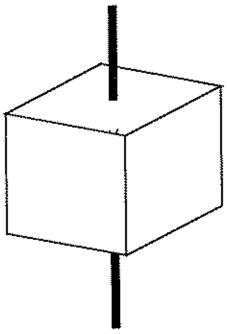


which would be extruded (pushed back) a certain distance (depth of cube) to form the solid.

Rotating it means to revolve the 2D outline around an imaginary axis so it also forms a solid. This rotation has a number of segments or slices that form the 3D object.

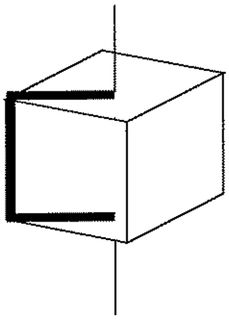
For example, to create a cube by revolution the imaginary axis (represented by the thicker line) would be:

Figure 14 - Cube's imaginary axis for revolution



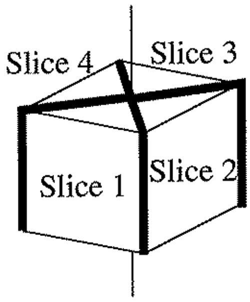
the outline would be:

Figure 15 - Cube's outline for revolution



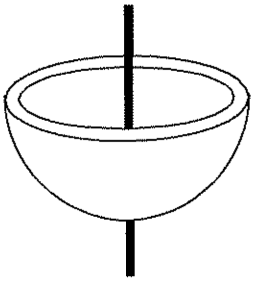
and the number of segments (slices) would be 4:

Figure 16 - Cube's slices



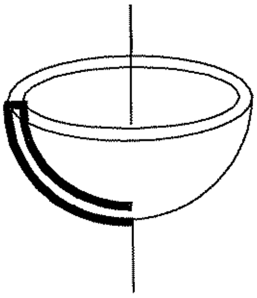
To create a fruit bowl the imaginary axis would be:

Figure 17 - Bowl's imaginary axis for revolution



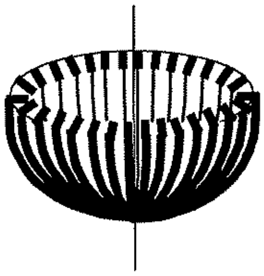
the outline would be:

Figure 18 - Bowl's outline for revolution



and the higher the number of segments (slices) the smoother the bowl would be (Figure 19).

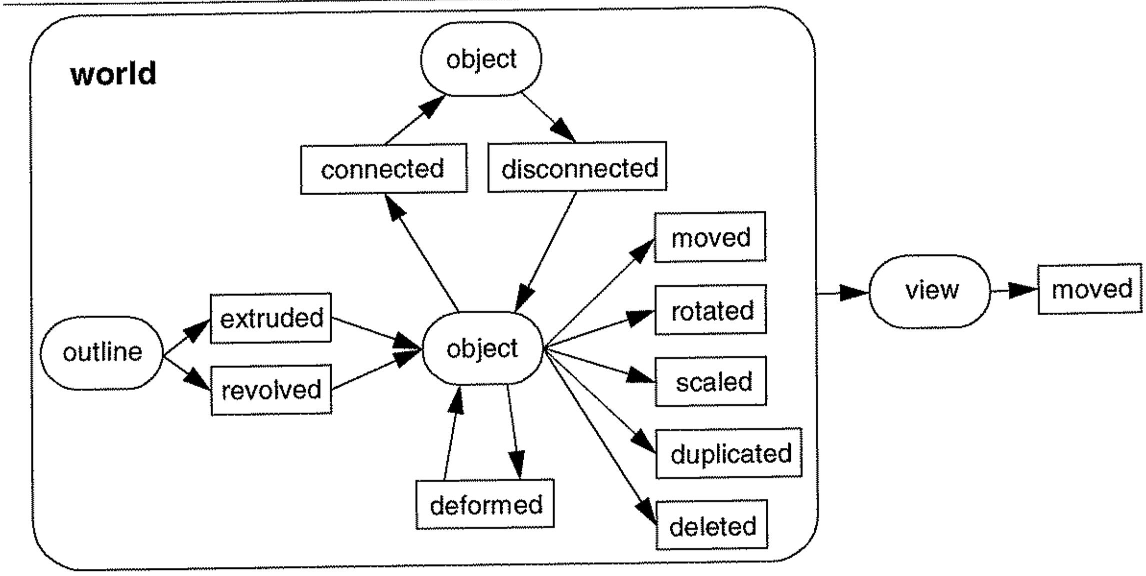
Figure 19 - Bowl's slices



On the other hand, objects can be *moved*, *rotated* or *scaled* in relation to the world, *duplicated* and *deleted*. Objects can also be *combined* or *deformed* to form other objects. Such objects in turn can be *looked at* from *different angles* and one can also get *closer* or *further away* from them.

The diagram below (Figure 20) summarizes these relationships between objects and operations.

Figure 20 - Basic Objects and Operations



In Figure 20 the round elements are objects and the square ones operations. Thus, an outline can be extruded or revolved to form a 3D solid object which in turn can be moved, rotated, scaled, duplicated or deleted. Objects can be connected to other objects then disconnected and also deformed. The world, where all the object exist in, can be viewed and this view can be moved.

Thus with these basic objects and operations in mind, which are common to all the applications used, other operations, which are specific to each of the applications, can and will be added in the following sections together with a description of how the user has access to these objects and operations, that is, the user interface.

Furthermore if the reader requires a more detailed explanation of the user interface s/he should refer to Appendix IV on page 131 which has a detailed tutorial for each of the applications.

4.4 Interactive Modeller (IM) and Interactive Deformable Modeller (IDM)

Since IM and IDM, the author's applications, are in fact the same application being used with different options they will be described as one and the difference, which is when deforming objects, will be described separately.

4.4.1 IM/IDM's Objects and Operations

IM/IDM shows a certain, empty, part of the *World* using *perspective view* plus the same portion of the world as viewed from the *front*, *top* and *side* using orthographic projection.

These views can be moved and *rotated.*

An *outline* can be put in any of the three different projections and it will be *extruded* or *rotated* to form a 3D solid object.

An object, apart from the operations which have been mentioned in the basic user model, can also have segments of it *cut off* or be *split*, resulting in two objects.

Objects can also be combined, or *connected*, to form other objects. Such connection is made by *glueing* one object to another at a single point. That is, each of the objects to be glued are selected by one of their points. As soon as the second object is selected the first one is brought towards the second and they became glued by the selected points. Although the glued objects move together as if one object they rotate and scale as separate ones. That is, as the objects are glued by a single point one of the objects can be rotate around that point while the other remains still, and similarly one of the object can be scaled while the other will remain the same size.

Another way which objects can form other objects is through *deformation*. An object can be deformed, that is, an object can have part of its boundaries placed in a different position relative to the object as a whole so as to deform its shape. And this is where IM differs from IDM. In IM when a certain part of a boundary is *moved* away from its initial state it does not inflict any changes on its neighboring parts. IDM uses the concept of *forces applied* to the object in order to have its shape changed, a change which affects the object as a whole.

4.4.2 IM/IDM's User Interface

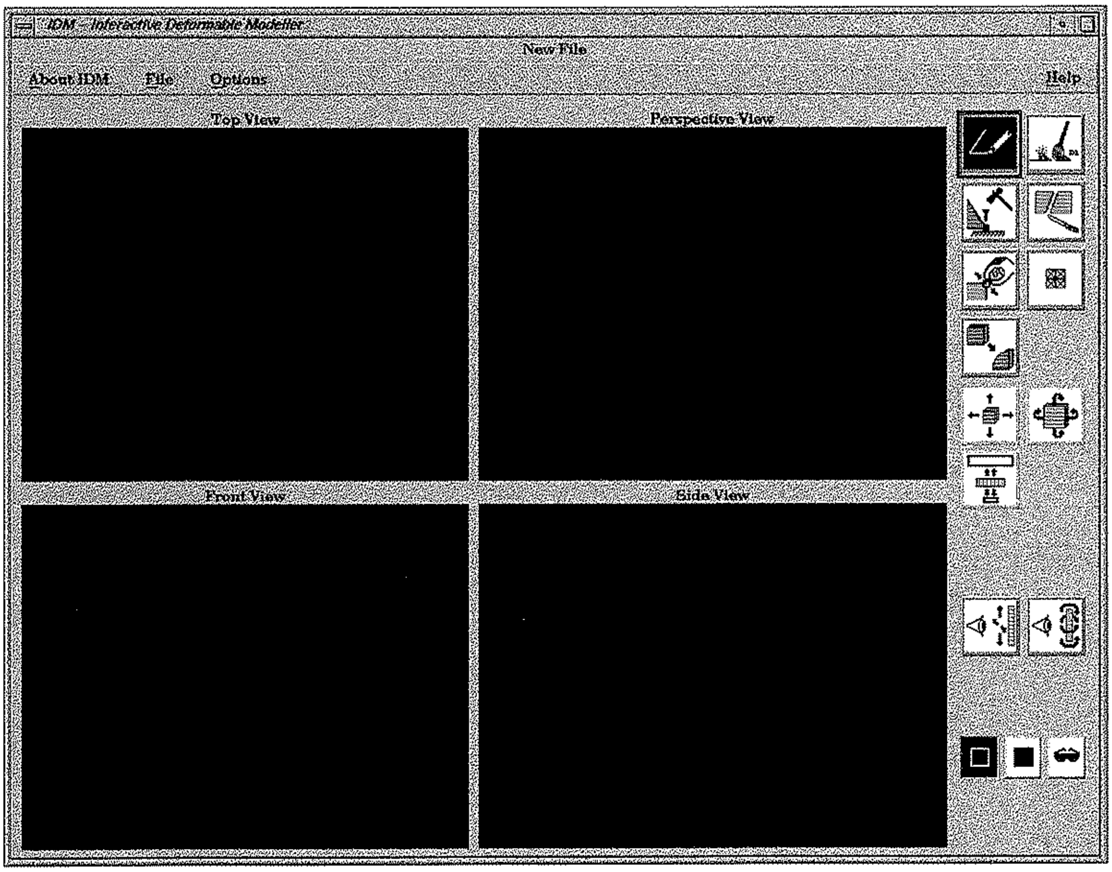
Now that the objects and operations for IM/IDM have been presented, one can explore the way a user has access to them, that is, the user interface.

IM and IDM interfaces are indeed the same apart from the need to support the additional functionality (in fact represented by two extra icons provided in IDM). So, as in the objects and operations section both interfaces will be described together and their different aspects regarding the deformation of objects will be presented last.

Figure 21 and Figure 22 show respectively IM and IDM screen display.

Figure 21 - IM's layout

Figure 22 - IDM's layout



In anti-clockwise order from the top left hand corner, the four black centred squares represent the top, front, side and perspective view. To their right there are four groups of icons and above them a menu bar.

The first group of icons (with green outline) contain the tools for creation of outlines, connecting, disconnecting, cutting, adding vertices and in the case of IDM applying forces. The second group (yellow outline) allows the user to move, rotate and scale objects. The third group (blue outline) allows the views to be moved and rotated. And finally, the fourth group (red outline) determines how the object is viewed, that is, as a wire-frame structure, shaded or stereoscopic.

The other operations which can be applied to objects, that is, duplication and deletion, are available through a menu under the *Options* menu bar.

Selected icons are shown in black background and the operations they perform are applied mainly: to a vertex, an object or the world.

To draw an outline the user first selects the *pencil* ✎ icon and using the mouse clicks the left mouse button where s/he wants the points to be. If the outline is closed, that is, the first and last points are the same, the outline is extruded, i.e. pushed back a certain amount. If, on the other hand, the outline is open, that is, the first and last points are not the same, the outline is revolved around an imaginary axis formed between the first and last points.

Once the object is created it can be *moved*, *rotated* or *scaled* by selecting the appropriate icon and using the mouse to click on the object which is to receive the operation. When this happens the object's colour becomes red to indicate that the object has been selected and *picked up*.

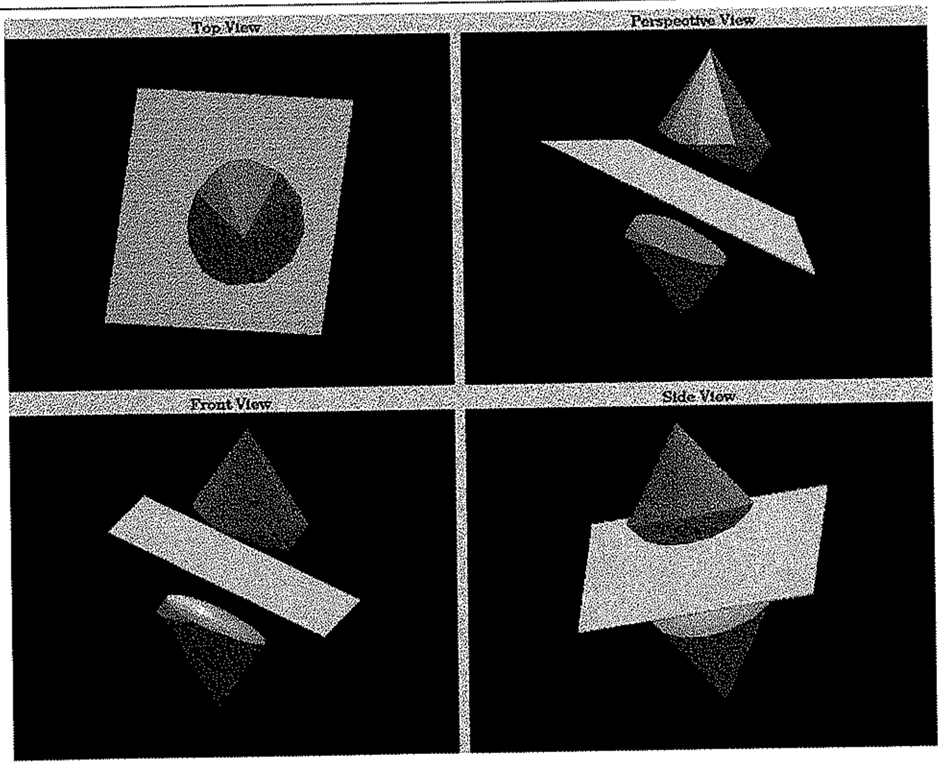
An object can also be *duplicated* by selecting *Duplicate object* under the *Options* menu and using the mouse to click on the object to be duplicated. The new object will appear slightly displaced on top of the original one.

An object can then be *connected* to another by selecting the *hammer* icon then using the mouse to click on a vertex of one object then on a vertex of the second object. The first object will then move towards the second object and be *glued* by the selected vertices which become the same and is represented by a white dot. To *disconnect* them the user selects the *broom* icon then clicks on the object s/he wants to disconnect, the white dot will disappear implying that the objects are disconnected.

An object can be deleted by choosing *Delete object* under the *Options* menu then using the mouse to click on the object to be deleted.

An object can also have parts *cut off* or be *split* resulting into two objects. By clicking once on the *knife* icon an infinite cutting plane appears. The user can then position the object or the plane as s/he wishes and when the object is ready to be cut the user clicks on the knife icon again and once the object is cut, one of its parts appears with the colour red and the other blue (Figure 23).

Figure 23 - IM and IDM cutting tool

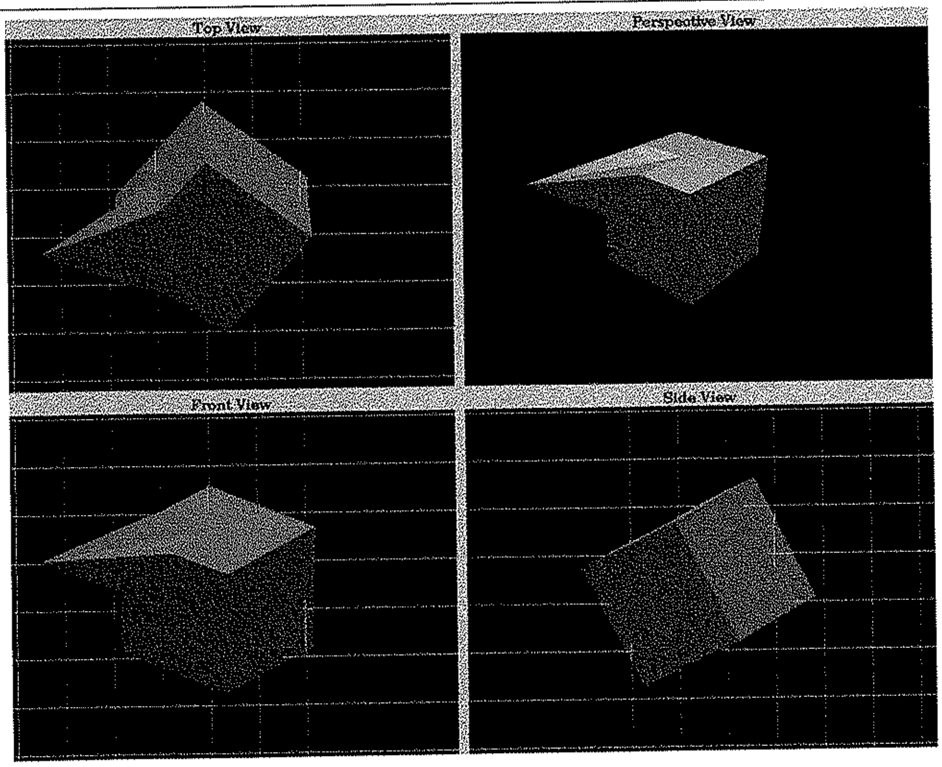


So that object(s) can be looked at from different angles, the camera, that is, the angle the user looks at the portion of the world where the object is, can be changed by selecting the *move camera* or *rotate camera* icons. After they are selected the user clicks anywhere on the black screens to move/rotate the camera which affects all the objects in the world.

Another operation which affects all the objects is the way they can be displayed, i.e. as *wire-frame* □, *shaded* ■ or *stereoscopic* . The user just clicks on the appropriate icon and the objects are displayed accordingly.

And finally an object can be *deformed* to form other objects. In terms of deformation the two applications work in different ways, IM, the author's geometrical application, *moves vertices* whereas IDM, the author's physical application, *applies forces* to them as described in Chapter 3. In IM the user moves a vertex, or a group of them, by first making sure that no icon is selected, i.e. in black background, then s/he uses the mouse to pick the vertex s/he wants to move. The selected vertex is highlighted with a white dot and starts to follow the mouse movements. When the user wants to 'let it go' s/he just clicks the mouse again and the vertex will stay where it is. Figure 24 shows an example of such an operation where a cube had one of its corners moved away from its initial state.

Figure 24 - IM's deformation of an object

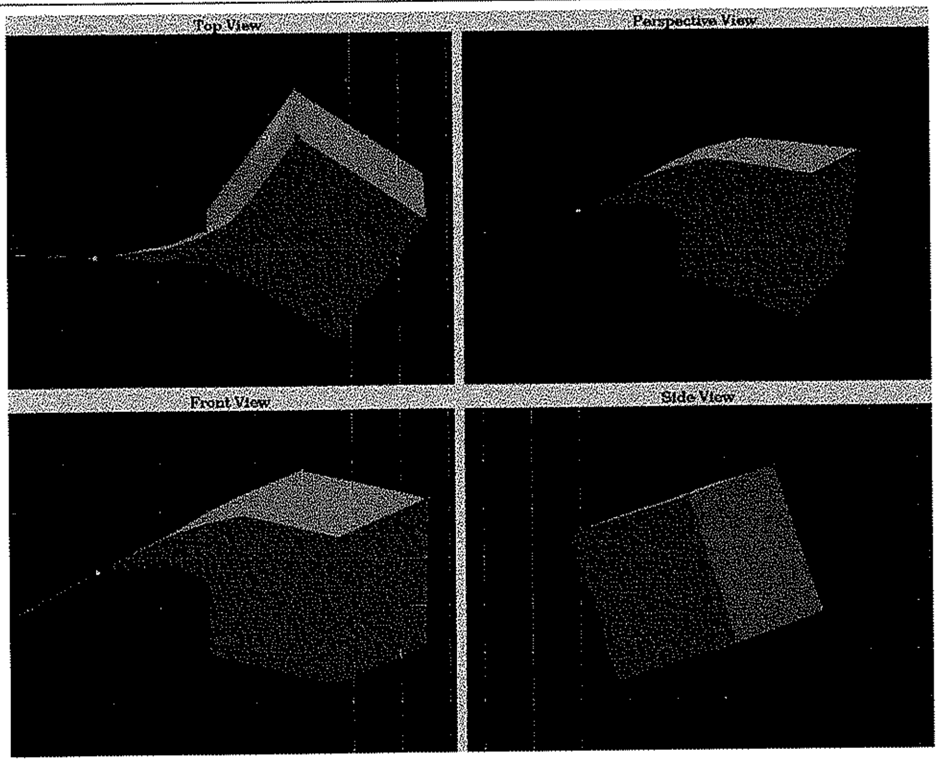


However, when the user moves a vertex s/he is just assigning to that vertex a new position with no consequences to neighbouring vertices. Here IDM differs from IM in a sense that when a force is applied to a vertex it's new position will affect neighbouring vertices. Vertices are displaced by the concept of *applying forces* of a certain *intensity* and *direction*, this results in a move (as in reality) which affects the object as a whole. In order to apply such a force the user first needs to define at least two fixed points on the object. S/he does that by selecting the *hammer* icon and then clicking on the desired vertices which will appear as a blue dot. Once the fixed vertices are defined the user can define which vertex/vertices will receive a force, its intensity and direction. To do so the user first selects the *force* icon then uses the mouse to click on the desired vertex which will appear as a green dot. A line will then appear from the vertex to the tip of the cursor and will follow its movement. This line's length represents the intensity of the force whereas its direction represents the force's direction. Once the user is satisfied with the position of the force s/he can click the mouse again and the force will be defined hence the line will stop following the cursor. At any moment the user can pick the force up again, in any of the orthogonal views and change its position, so using all the three orthogonal views allows the user to define the force with its three degrees of freedom. Once the fixed points and forces are defined the user clicks the *apply* icon to start applying the forces and clicks on it again to stop. Figure 25 shows an example of such deformation where the green line represents the amount (length) and direction of the force applied to the vertex (green square). As the force applied is intentionally in a direction similar to the one which was used as an example for the deformation of an object in IM (Figure 24) the reader can compare them to see the different outcome.

In IM, the geometrical application (Figure 24), the vertex was moved away from its initial position while maintaining the relationship in the structure, that is, all elements which shared the vertex moved with it. In doing so the move looks artificial because of the appearance of right angles and unnatural movement like the groove on the top face as can be seen in the perspective view.

In IDM, the physical application (Figure 25), a pull force was applied to the vertex resulting in a more smoother and natural deformation with no unexpected grooves.

Figure 25 - IDM's deformation of an object



Finally, because vertices are so important when connecting and deforming objects (both in IM and IDM) there is one last operation which can be applied to the object: the addition of more vertices to its structure. This is achieved by clicking on the *meshing* ▩ icon and the selected object (represented in red) will have more vertices added to its structure by subdividing the existing mesh.

4.5 Interactive 3D Modeler (I3DM)

4.5.1 I3DM's Objects and Operations

As some of I3DM's objects and operations are similar to IM's objects and operations they are not going to be described again and the reader should refer back to Section 4.4.1 on page 53 for further explanations.

I3DM presents the user with four views of the World: *perspective, front, top* and *side* views, and although all views can be moved just the perspective one can be *rotated.*

An *outline* can be put in any of the three latter views mentioned and it will be *extruded* or *rotated* to form a 3D solid object.

Just the operations mentioned in the basic frame can be applied to an object, that is, compared to IM/IDM objects cannot be *split* into two or have bits *cut off.*

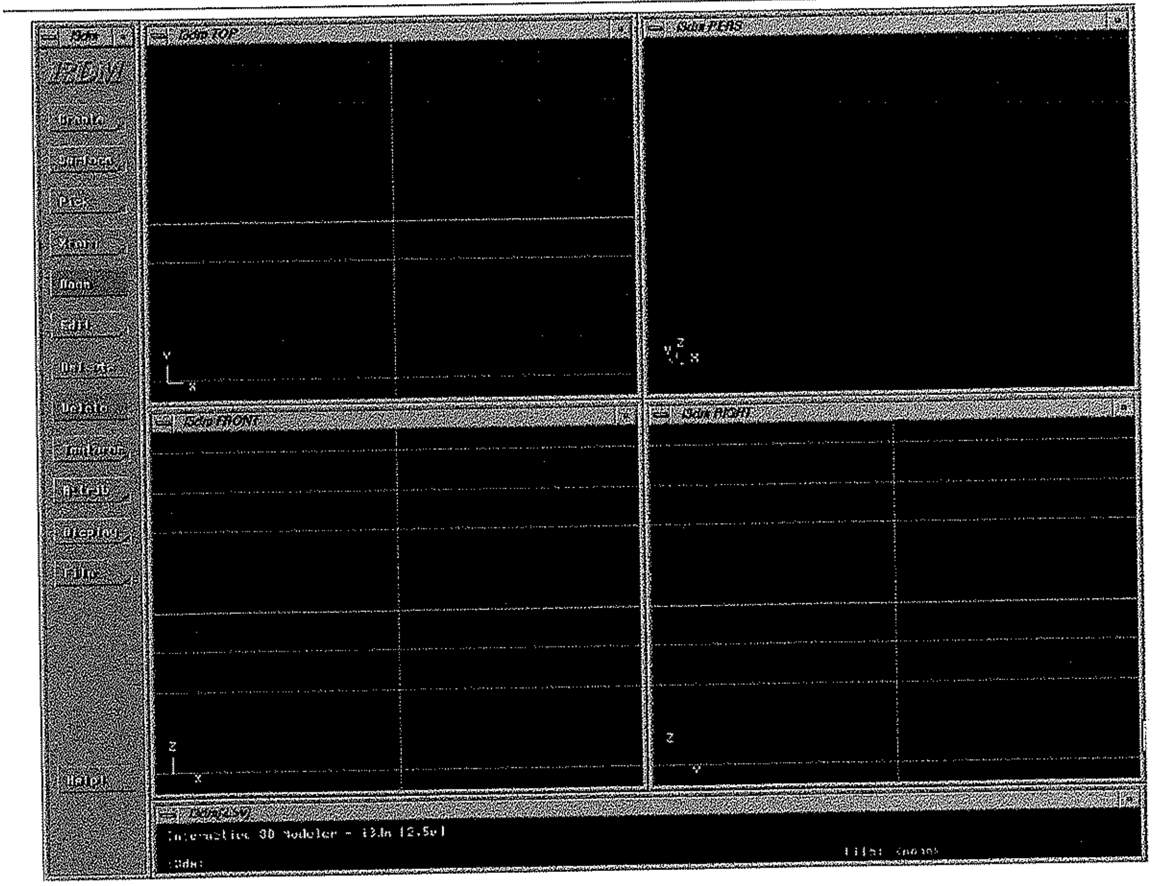
Objects are combined, or *connected,* by *grouping* objects together so if an operation is done to an object all the objects in which group that objects belong to will be affected.

As in IM, *deformation* of an object is done by *moving* a certain part of a boundary away from its initial state which does not inflict any changes to neighbouring parts.

4.5.2 I3DM's User Interface

Now that I3DM's objects and operations have been described the reader can be guided through its user interface. Figure 26 shows I3DM's screen layout.

Figure 26 - I3DM's screen layout



In anti-clockwise order from the top left hand corner, the four black centred squares represent the top, front, right side and perspective view. To their left there are a number of labelled buttons, some of which bring up menus, and below them a command line window.

Not all the buttons are of interest to this work, just the ones labelled *Create*, *Surface*, *Pick*, *Xform*, *Edit* and *Delete*. *Create* refers to the creation of the outline. *Surface* for extruding, revolving and making a face of an outline. *Pick* for selecting and de-selecting objects or vertices. *Xform* for moving, rotating, scaling and copying objects and to move the pivot point used for the revolution of the outline. *Edit* for grouping and un-grouping objects and *Delete* to delete current selected object(s).

To draw an outline the user first selects *Line* under the *Create* menu and using the mouse clicks where s/he wants the points to be. If the outline is to be extruded the user first needs to make it as a face, that is to transform it from just a set of lines into a closed polygon, by selecting *Face* under the *Surface* menu. Once that is achieved the user can than create another line which will be the guide for the extrusion. And finally to extrude the object the user selects *Extrude Along* under *Extrude* under the *Surface* menu. On the other hand if the user wants the outline to be revolved, s/he needs first to move the pivot which is the centre of rotation so it coincides with the first or last point in the outline. To do so the user selects *Move pivot* under the *Xform* menu and using the mouse clicks and holds it to move the green cross which represents the pivot. Finally the user selects *Revolve Z* (assuming the outline has been drawn in the front view) under *Revolve* under the *Surface* menu and then press return.

Once an object is created it becomes the current object (represented by having its wire-frame structure drawn in yellow), the user then can select *Move*, *Rotate*, *Scale uniform* or *Scale Non-uniform*, or *Copy object* under the *Xform* menu to apply the operations to an object by clicking and holding the mouse button in any of the views. However, if the desired object is not selected (yellow) the user first needs to deselect all objects by selecting *Nothing* under the *Pick* menu, select *Object* again under the *Pick* menu and then click on the desired object.

One or more objects can be combined, or grouped, to form another object. This is done by first selecting the objects which will be grouped using the *Pick* menu then selecting *Group* under the *Edit* menu. Grouping means that if one object in the group is picked all are, so any operations are done to the whole group and one consequence of this is that the objects cannot be moved, rotated or scaled independently of the others.

Objects can be disconnected by first picking a group and then selecting *Ungroup* under the *Edit* menu.

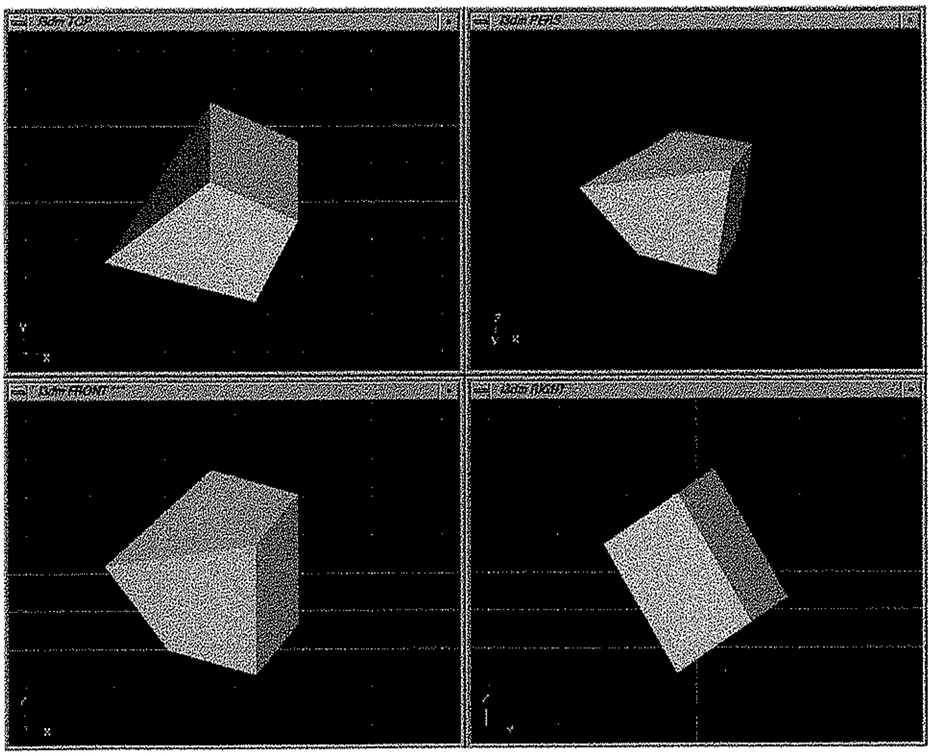
Objects can also be deleted by picking them first and then clicking the *Delete* button.

So that object(s) can be looked at from different angles, the parameters of the camera model, can be changed interactively by using the mouse buttons inside the views. However, only the perspective view can be rotated and moved whereas the front, side and top views can be moved only.

Objects can be displayed as a wire-frame or shaded by clicking a mouse button in the view window which it is to be changed, a menu will appear and the user should select or de-select the shade option.

And finally an object can be deformed to form other objects. I3DM's deformation follows the same concept of moving vertices which IM uses. Once the object is built the user can deform it by first selecting which vertices s/he wants to move. This is done by selecting *Vertex* under the *Pick* menu and using the mouse to click on the desired blue crosses in the wire-frame structure which represent vertices. To move them the user selects *Move* under the *Xform* menu and uses the mouse to re-position the vertices. Figure 27 shows an example of such a deformation where a cube had one of its corners moved as in the example given in IM (Figure 24).

Figure 27 - I3DM deformation of an object



4.6 Swivel3D Professional

4.6.1 Swivel3D's Objects and Operations

Apart from the basic objects and operations (described in Section 4.3 on page 49) Swivel3D has a design object concept which involves *sections*. As in architectural drawings an object is seen as a set of sections: *cross*, *side* and *top sections*.

Hence two outlines are necessary when creating an object, one for the cross section and another for the side and top sections which are updated simultaneously. Moreover these sections are not part of the world so when its design is finished, the object needs to be put into the world so operations can be applied to it. So there are two distinct areas: the *design* and the *world*.

Once the object is in the World only the operations mentioned in the basic frame can be applied to an object, that is, compared to IM/IDM, objects cannot be *split* into two or have segments of it *cut off*.

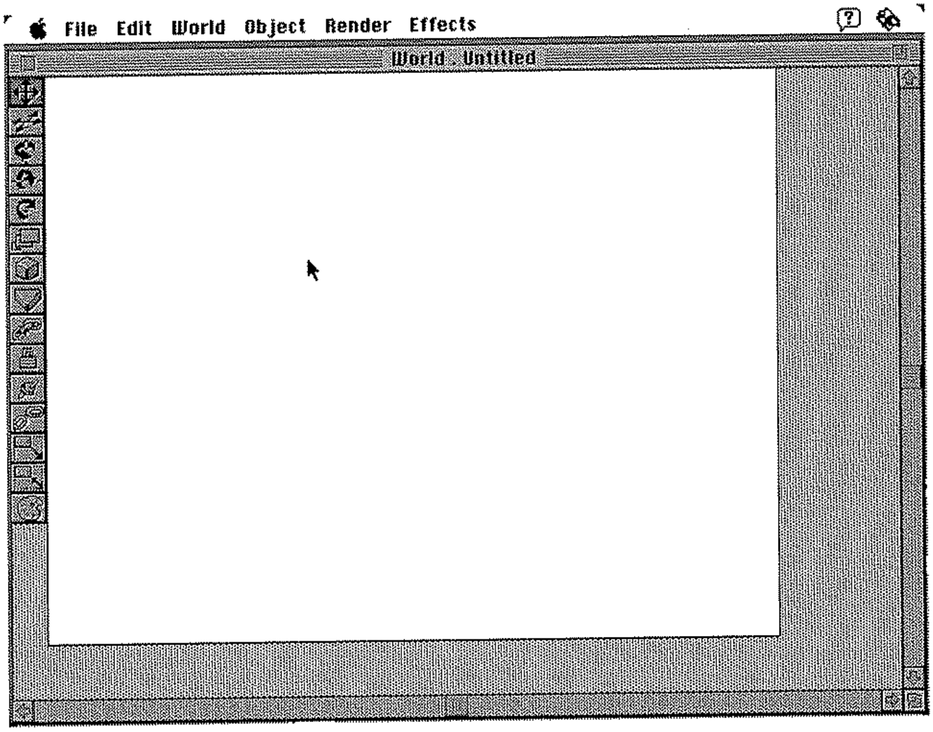
Objects can be combined, or *linked,* in three different ways. However when a link is performed it maintains a distinction between the objects it links by having a *child* and *parent* relationship. The *child* is the first object chosen and the *parent* the second. The first link allows the child to move and rotate freely on its own but when the parent is moved or rotated both, parent and child, will do so. The second link locks both parent and child together so they always move, rotate and scale together. The third link allows both to rotate independently but they move together.

Deformation of an object is done by first taking the object back to its design status. There the object can have new outlines drawn on its sections or have its existing outlines deformed by displacing part of them. The object then is put back into the world where it can be shaded and view from different view points.

4.6.2 Swivel3D's User Interface

As described in the previous section, Swivel3D has two different areas: the *design* and the *world,* for which it has two separate lay-outs. The user is first faced with the empty world as shown in Figure 28.

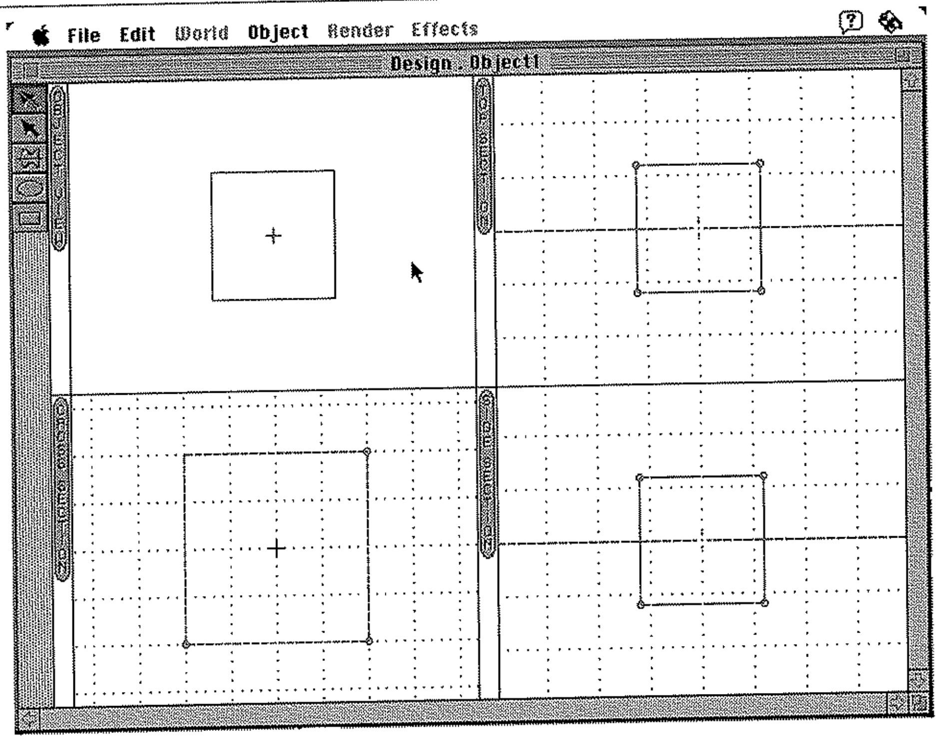
Figure 28 - Swivel3D's world view



The white window represents the world, to its left there is a set of icons and above a menu bar. Since an object cannot be design directly in the world, the icons represent all the operations that can be done to objects apart from duplicate object (which is through the Edit menu) and delete object which can be done through the keyboard or Edit menu.

In order to create a new object the user first selects *Design new Object* under the *Object* menu and the design screen will appear (Figure 29).

Figure 29 - Swivel3D's design screen



The three white squares with the dotted grid on them represent the three sections: *cross*, *side* and *top* as viewed anti-clockwise from the bottom left corner. The fourth white square on the top left corner represents the view of the whole object as positioned in the world or as seen front, side and top according to which section the user is working with.

An outline can be drawn by first selecting the *polygon*, *oval* or *square* icon. The polygon icon allows the user to draw a free shape polygon in the cross section but in the side and top sections there is a line of symmetry which forces the user to draw a symmetric shape, that is, both sides of the horizontal line (Figure 29) are identical. Once the drawing is completed in the side or top section, the other section (top or side) will be updated so when an outline is drawn both the side and top sections have the same outline. A circle or a square of fixed size is drawn in the cross section after the user selects the appropriate icon and clicks once on the cross section. On the side or top section the user can click, hold and drag the mouse so it draws a circle or square where the moving up or down defines its width and left or right defines its height.

Extrusion in Swivel3D is achieved by using the cross section to draw the desired 2D outline and then draw a square on the side section of required height and width which will govern the extrusion. *Revolution* on the other hand is achieved by a circle in the cross section and the 2D outline drawn horizontally on the side section.

Once the object is designed the user can bring it to the world by closing the design window.

Once in the world the object can be *moved* , *rotated* or *scaled* by selecting the appropriate icon and using the mouse to click and drag the object as required.

Objects can be *duplicated* by first clicking on the object so it becomes selected (so it starts flashing) then the user selects *Duplicate object* under the *Edit* menu and the new object is placed at some distance away from the original one.

Objects can also be combined, or *linked*. The three types of link are called *simple* (if child moves it moves alone, otherwise both parent and child move), *lock* (both locked) and *ball joint* (if child rotates it rotates alone, otherwise both rotate). To use them the user first selects the appropriate icon and using the mouse drags a line from the *child* to the *parent* object which will flash indicating that the operation was completed successfully. To break the link the user selects the *disconnect* icon and click on the object to be separated.

The world cannot be interactively rotated but the user can change the position s/he is looking at it by selecting *front*, *back*, *right*, *left*, *top* or *bottom* under *World View* under the *World* menu.

Zooming in and *out* are achieved by selecting the appropriate icon and clicking and dragging the world.

And finally the object can be *deformed* by changing its original outline. To do so the user first double click on the desired object in the world which will bring back the design screen. Once in the design screen the object can be deformed by moving its vertices. The vertices are the points the user clicked in order to form the shape in the appropriate section. Figure 30 shows an example where a cube is having its side section deformed by moving two of its vertices (points with a small circle on top). The changes can be symmetric, i.e. both sides of the axis, or not and also be or not reflected in the top section.

Figure 30 - Swivel3D's deformation of an object (design screen)

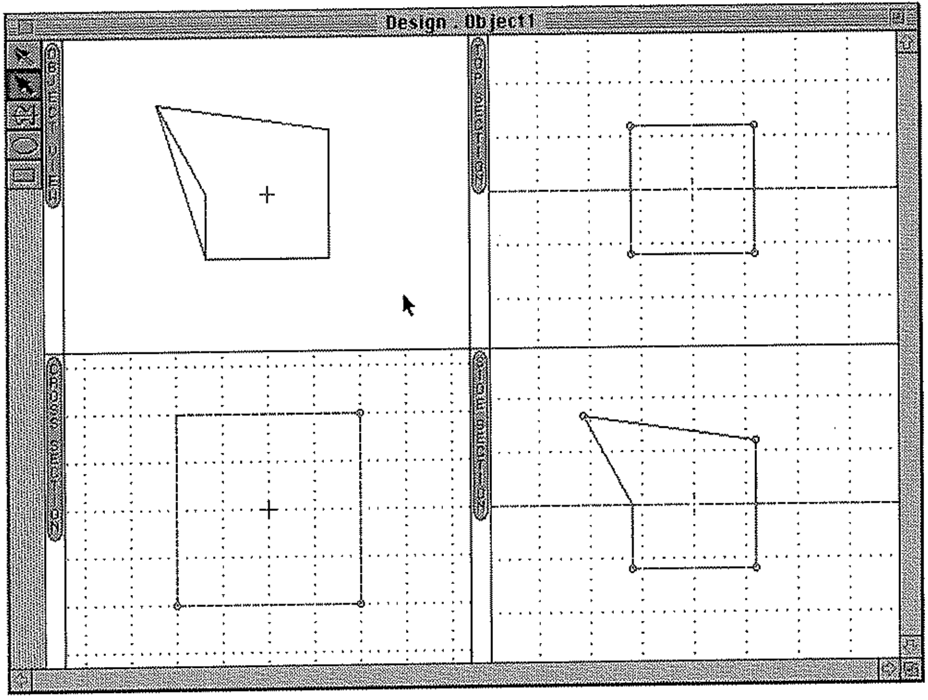
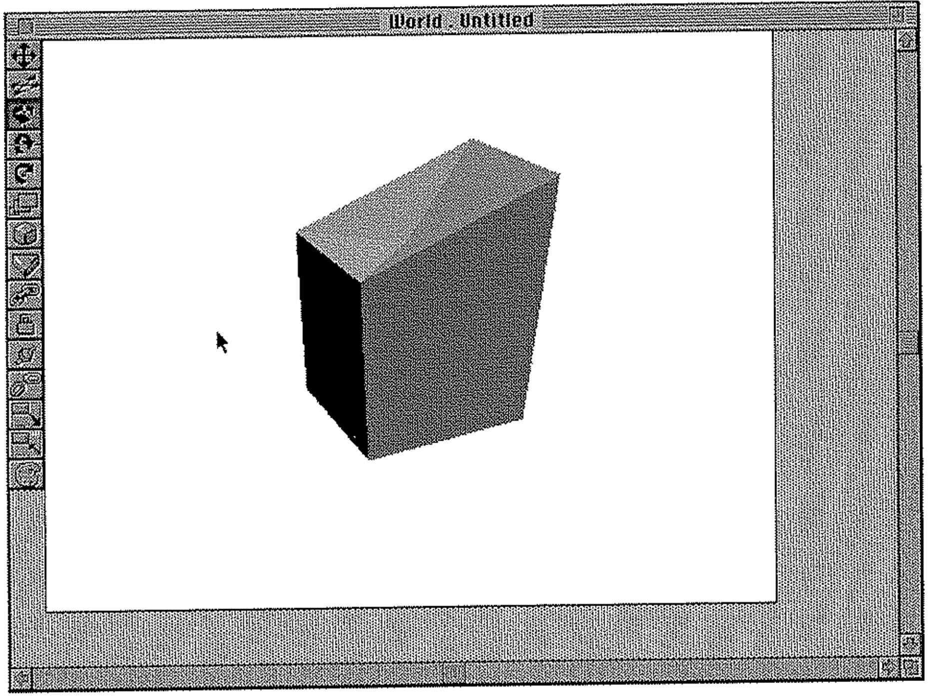


Figure 31 - Swivel3D's deformation of an object (world view)



4.7 Summary

In order to make it easier for the reader to visualize the different operations and the different number of them necessary for a given task on each of the applications, four scenarios are described below. These four scenarios are: build a long rectangle using extrusion, built a cone with a diagonal cut, build a chair by joining objects made by revolution, build a tulip by deformation.

Table 1 below shows the necessary operations for the creation of a long rectangle by extrusion. Typically a square is drawn and pushed back a certain distance.

Table 1 - Scenario 1: build a long rectangle using extrusion

IM/IDM	I3DM	Swivel3D
1. select parameter in menu 2. define depth of extrusion 3. select draw icon 4. draw a square clicking back on first point	1. select create line 2. draw square 3. select make face 4. select create line 5. draw line which defines depth of extrusion 6. select pick object 7. pick square 8. select extrude along 9. select pick object 10. pick line 11. select delete	1. select design new object 2. select draw rectangle icon 3. draw rectangle in side section which defines depth of square 4. close window to go back to world view

Table 2 below shows the necessary operations for the creation of a cone with diagonal cut. The cone is drawn by revolution. In IM/IDM it is cut diagonally. In I3DM all the points which form the base need to be moved into position. In Swivel3D just two points in the side section need to be moved into position.

Table 2 - Scenario 2: build a cone with diagonal cut

IM/IDM	I3DM	Swivel3D
1. select draw icon 2. draw a half triangle double clicking on the last point 3. select cut icon 4. select move or rotate object icon 5. position cutting plane 6. select cut icon	1. select create line 2. draw a half triangle on front view 3. select move pivot 4. move pivot on top of first or last point 5. select revolve around Z 6. press return 7. select pick vertex 8. pick a vertex from base 9. select move 10. move vertex to position 11. select pick nothing 12. repeat 7 to 11 until base is diagonal	1. select design new object 2. select draw ellipse icon 3. click on cross section 4. select draw polygon icon 5. draw triangle on side section double clicking to finish 6. select move vertex icon 7. move points from base of triangle so to make base diagonal 8. close window to go back to world view

Table 3 shows the creation of a chair by joining squared objects made by revolution.

Table 3 - Scenario 3: build a chair by joining objects made by revolution

IM/IDM	I3DM	Swivel3D
1. select parameters in menu	1. select create line	1. select design new object
2. set number of slices to four	2. draw half a square in front view to make seat	2. select draw rectangle icon
3. select draw icon	3. select move pivot	3. draw thin rectangle in side section which defines depth of seat
4. draw half a square to make seat double clicking on last point	4. move pivot on top of first or last point	4. close window to go back to world view
5. draw half a square to make leg double clicking on last point	5. select revolve around Z	5. click on empty world so to deselect object
6. select duplicate object	6. type seg 4 and press return	6. select design new object
7. repeat 6 three times	7. select create line	7. select draw rectangle icon
8. select rotate camera	8. draw half a square in front view to make leg	8. draw long rectangle which defines length of leg
9. position camera so to see vertices better	9. select move pivot	9. close window to go back to world view
10. select join icon	10. move pivot on top of first or last point	10. select duplicate
11. click on vertex of leg	11. select revolve around Z	11. repeat 10 three times
12. click on vertex of seat	12. type seg 4 and press return	12. select move object icon
13. repeat 9 and 10 for other three legs	13. select copy object	13. position leg on seat
14. select rotate object	14. select move	14. repeat 13 three times
15. adjust legs if necessary	15. move new leg	15. select lock icon
	16. repeat 11 to 13 three times	16. lock objects together
	17. select pick object	
	18. pick a leg	
	19. select move	
	20. position leg on seat	
	21. select pick nothing	
	22. repeat 15 to 19 three times	
	23. select pick all	
	24. select group	

Table 4 shows how each package operates the deformation. In this example all start with an object like a wine glass without base. The petals then are made by pulling the top of the wine glass.

Table 4 - Scenario 4: build a tulip by deformation

IDM (physical)	IM (geometrical)	I3DM	Swivel3D
1. select draw icon 2. draw a half wine glass without base double clicking on the last point 3. select fix icon 4. click on at least two vertices to be fixed 5. select force icon 6. click on vertex at top, line follows 7. click again to define force 8. repeat 6 and 7 three times 9. select apply force icon 10. select apply force icon to stop when desired 11. select clear forces icon	1. select draw icon 2. draw a half wine glass without base double clicking on the last point 3. deselect draw icon 4. click on vertex from top of glass 5. move point to position 6. click to define position 7. repeat 4 to 6 three times	1. select create line 2. draw a half wine glass without base on front view 3. select move pivot 4. move pivot on top of first or last point 5. select revolve around Z 6. press return 7. select pick vertex 8. pick a vertex from top 9. select move 10. move vertex to position 11. select pick nothing 12. repeat 7 to 11 three times	1. select design new object 2. select draw ellipse icon 3. click on cross section 4. select draw polygon icon 5. draw wine glass without base on side section double clicking to finish 6. select move vertex icon 7. move a point from top of glass just on side section 8. close window to go back to world view 9. select duplicate 10. select rotate icon 11. rotate object so pair of petals fill gap on the other object 12. select lock icon 13. lock objects

The table below shows the different concepts presented and the main differences among the four applications described.

Table 5 - Comparison of applications used

	IM	IDM	I3DM	Swivel3D
Front, side, top and pers. view	◆	◆	◆	
Single view				◆
Cross, side and top section				◆
Menus for interface	◆	◆	◆	◆
Icons for interface	◆	◆		◆
Use of buttons in mouse	2	2	3	1
Camera rotation	◆	◆	◆	
Move vertices	◆		◆	◆
Apply forces		◆		
Grouping			◆	◆
Direct connection	◆	◆		
Cut	◆	◆		
Machine type: Silicon Graphics	◆	◆	◆	
Machine type: Macintosh				◆

IM, the author's geometrical application, IDM, the author's physical application, and I3DM allow the user to work with four views of the world whereas Swivel3D has just a single one. Swivel3D is the only one which uses the concept of cross, side and top section for the creation or deformation of new objects. All of them have menus and icons in their interface apart from I3DM which has only menus. IM and IDM work with two buttons of a three button mouse whereas I3DM uses all three and Swivel3D makes use of a single button mouse. The first three applications (IM, IDM and I3DM) have camera rotation whereas Swivel3D does not. IM, I3DM and Swivel3D use the concept of moving vertices when deforming an object whereas IDM uses the concept of forces. In I3DM and Swivel3D objects need to be brought together and positioned in their right places before they can be connected or grouped whereas in IM and IDM the objects are moved towards each other and glued by a point specified by the user and can at any time be scaled or rotated independently. IM and IDM have the extra concept of cutting. And finally, the first three applications (IM, IDM and I3DM) run on a Silicon Graphics machine whereas Swivel3D runs on a Macintosh.

This chapter presented an overview of the applications used in the proposed investigation. This overview will help the reader to understand the following chapters which present the investigation and its results.

Chapter 5 Evaluation

5.1 Introduction

The various applications were described in detail in the previous chapter. This chapter discusses the evaluation strategies and experimental design for testing the hypothesis described in Chapter 1. This stated that using the physical method of deformation would bring a significant increase in efficiency and user satisfaction over the geometrical method. Furthermore other assumptions were made: that there would be a difference between Arts and Sciences based students with respect to performance; that there would be a difference in spatial ability between these two groups, which could account for the possible difference in performance; and, that there could be a difference in performance which could depend on spatial ability.

The experimental method chosen is presented followed by the experimental design.

The experimental design is divided into sub-sections describing each of the elements used in the evaluation which were: a Visual/Auditory/Kinaesthetic questionnaire, a spatial ability test, an introduction sheet, a background questionnaire, a tutorial, an object representation, a questionnaire about each of the tasks performed, a questionnaire about the whole experiment and an observer's sheet. Where appropriate each description of an element incorporates its initial design, the problems, if any, encountered during pilot studies followed by its final design.

In total four sets of pilot studies were conducted, the first contained eight subjects and the subsequent ones four subjects each. Although changes needed to be made after each set, the more significant ones were identified after the first pilot study.

After the presentation of all the elements a section describes how the experiments were actually conducted, with a detailed description of the procedures followed.

5.2 Experimental Method

The main hypothesis required an analysis of differences between the two methods, physical and geometrical. This analysis however could be affected by the difference in functionality of the methods or the developed user interface or both. Any findings resulting from such an analysis could not be attributed to one cause or the other. Therefore another analysis to take place before the analysis of the methods was proposed. This first analysis compared the developed geometrical application with existing geometrical applications in an attempt to establish whether the developed user interface was of an acceptable standard in itself.

The first experimental design included the idea that a subject would use in the first analysis two geometric applications and in the second both methods, physical and geometrical, and be asked to draw a comparison between the two. However, when the pilot studies were conducted, this approach proved to be inadequate due to its great demand for a subject's attention and interest over a long period of time. Hence, it was decided that each subject would use just one application or method and independently of which all subjects would perform the same tasks. Since there were four applications, one physical and three geometrical, four sets of data were collected. The three sets of data from the geometrical applications formed the first analysis. The same data collected from the developed geometrical application together with the data from the developed physical application formed the second analysis.

The definition of the tasks to be performed started by establishing that at least two 3D graphical objects should be built, favouring each deformation method. However, the physical model could be divided into three actions: cutting, joining and deforming. Therefore, on the geometrical side, primitives and surfaces of revolution would form groups to counterbalance the physical side. So a list of objects was constructed and divided into six groups: primitives, truncated primitives, primitives with deformations, surfaces of revolution, composite objects and general objects.

The list per group is presented below. Together with it is a randomly chosen example of one of the objects of the group built in each of the applications used. Above each picture is also the approximate time in minutes which took an expert user (the author) to produce it, including object rotations.

Primitives included five solid primitive shapes: a tetrahedron, a sphere, a pyramid, a cone and a cylinder. In the following groups a cube, which was later used as a demonstration object, was also considered part of the primitive group.

Figure 32 - Primitive object (cylinder) built in IDM/IM (1 min.)

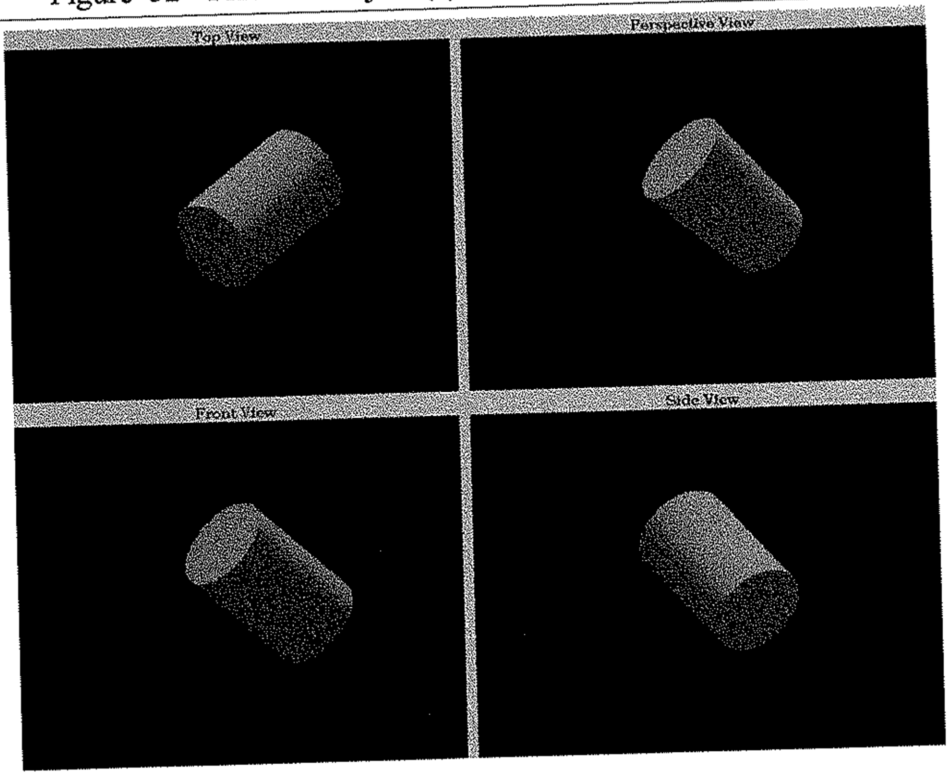


Figure 33 - Primitive object (cylinder) built in I3DM (1 min.)

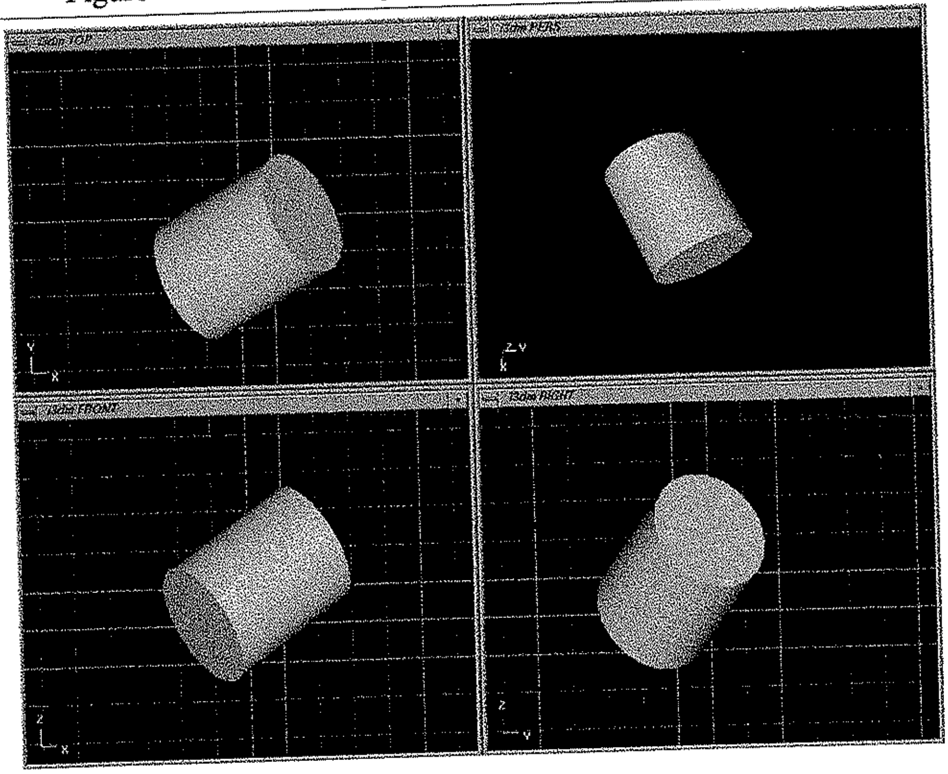
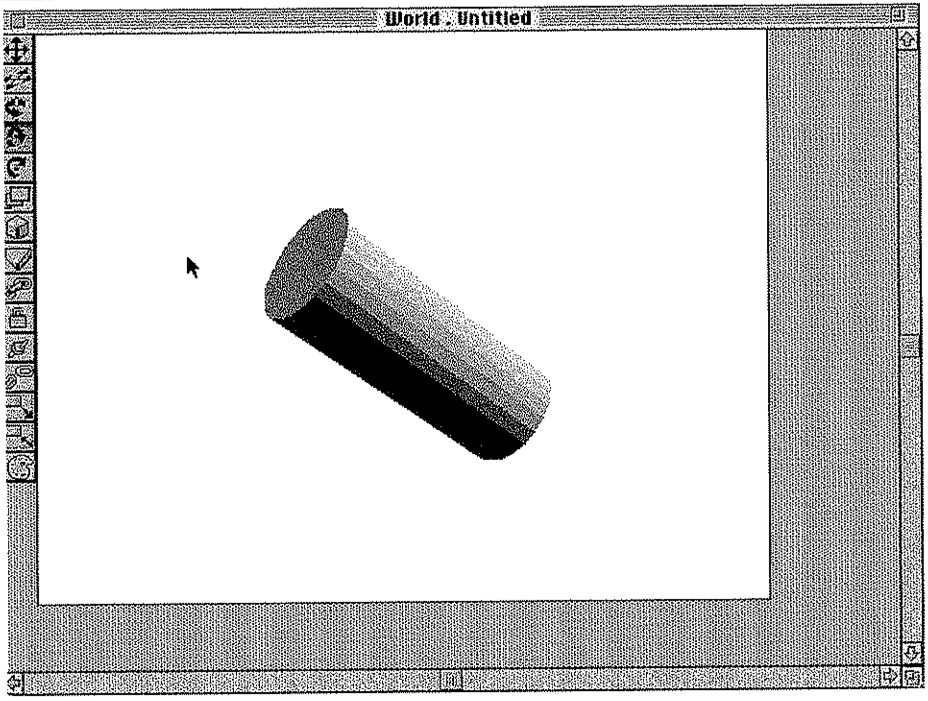


Figure 34 - Primitive object (cylinder) built in Swivel3D (1 min.)



The truncated primitive group contained six objects from the primitive group with a cut: a cube without a corner, a tetrahedron without two corners, an oblong with diagonal cut, a pyramid without a corner, a cone with diagonal base and a cylinder with diagonal cut.

Figure 35 - Primitive (oblong) with cut built in IDM/IM (4 min.)

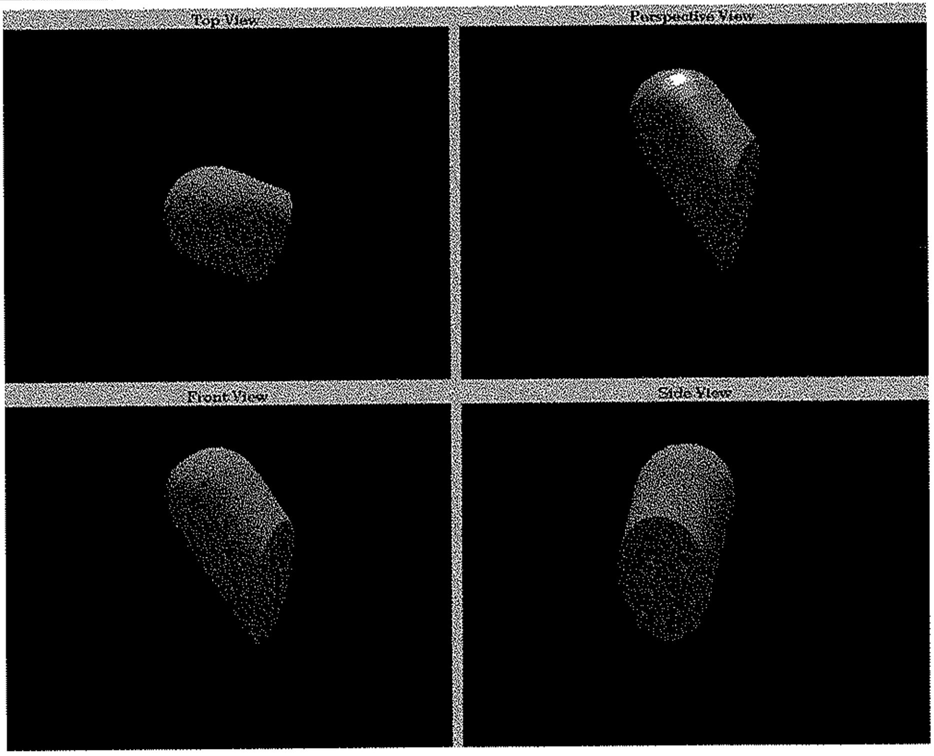


Figure 36 - Primitive (oblong) with cut built in I3DM (12 min.)

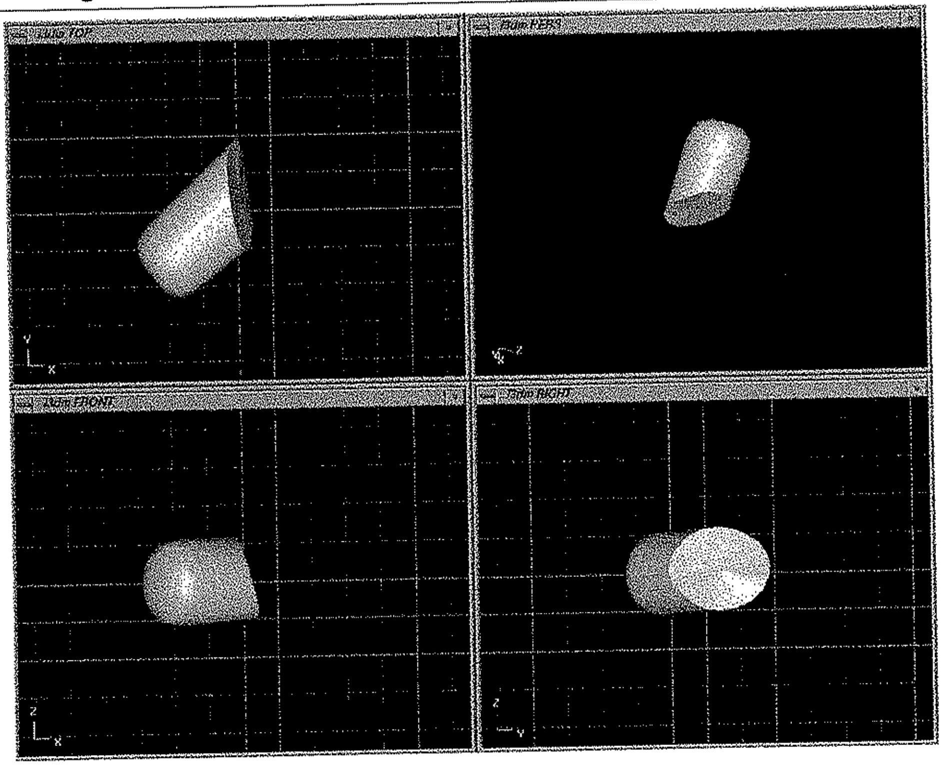
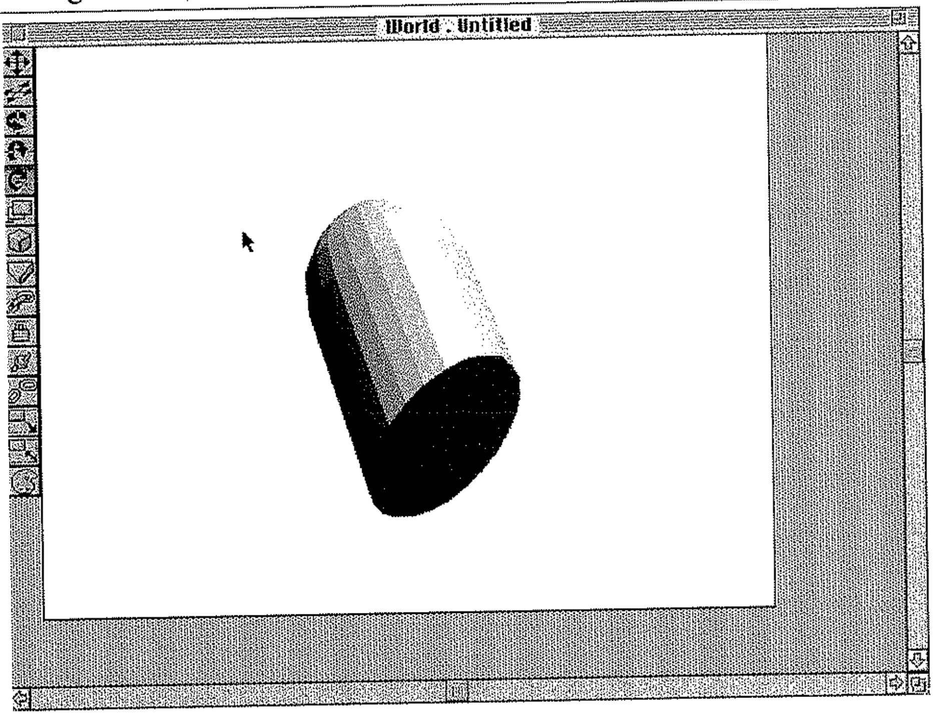


Figure 37 - Primitive (oblong) with cut built in Swivel3D (3 min.)



The primitives with deformations (later referred to as the "abstract" group) contained eight objects from the primitive group with a push or pull deformation: cube with a spike on three adjacent faces, a cube with two corners in, sphere with four spikes, pyramid with four spikes, pyramid with two corners in, cylinder with two opposite spikes, hexahedron with two corners in, octahedron with four spikes.

Figure 38 - Abstract object (octahedron with 4 spikes) built in IDM (4 min.)

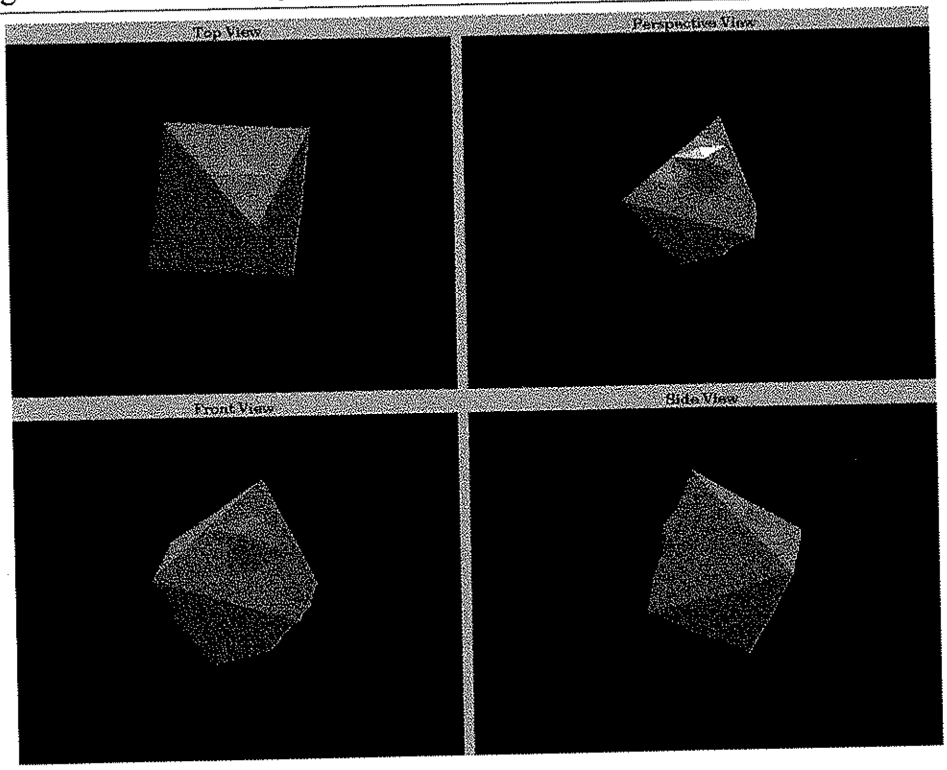


Figure 39 - Abstract object (octahedron with 4 spikes) built in IM (6 min.)

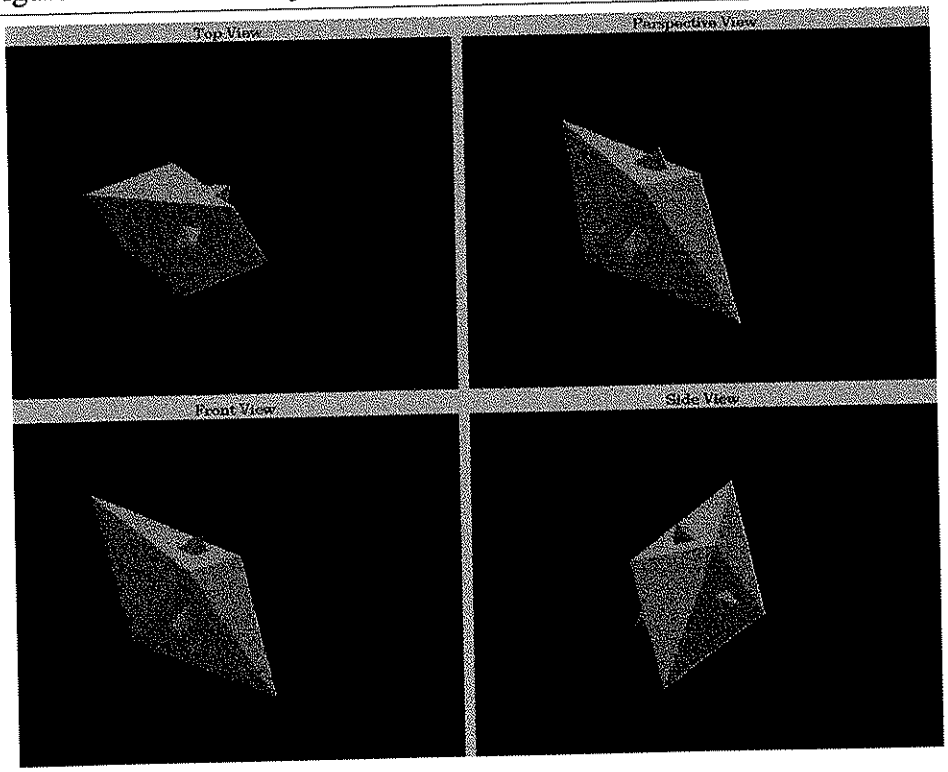


Figure 40 - Abstract object (octahedron with 4 spikes) built in I3DM (10 min.)

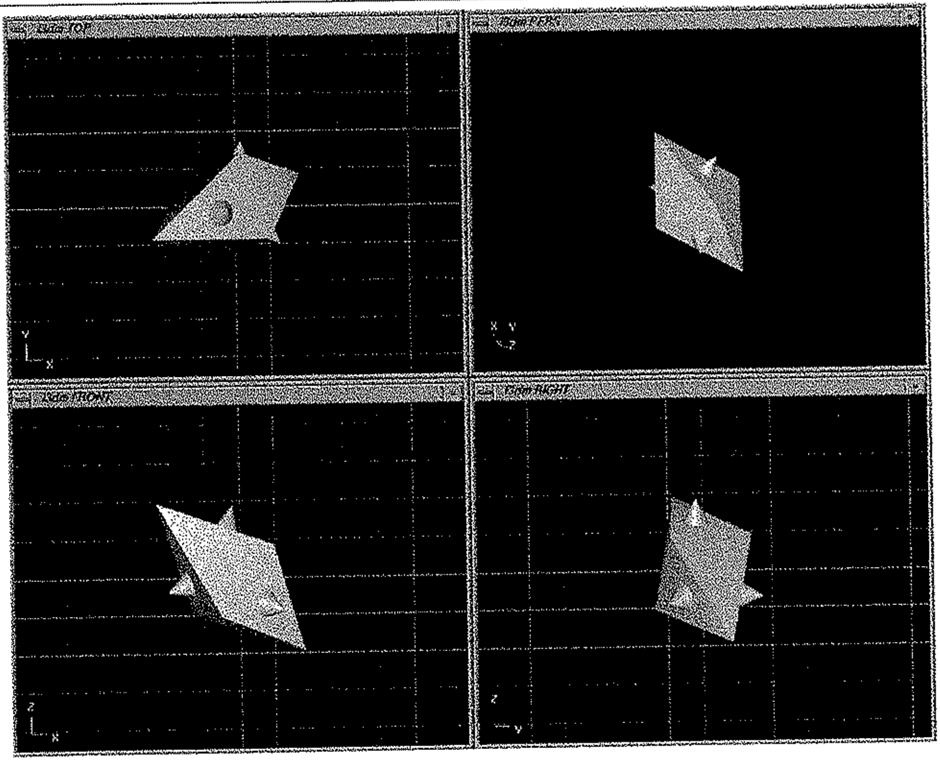
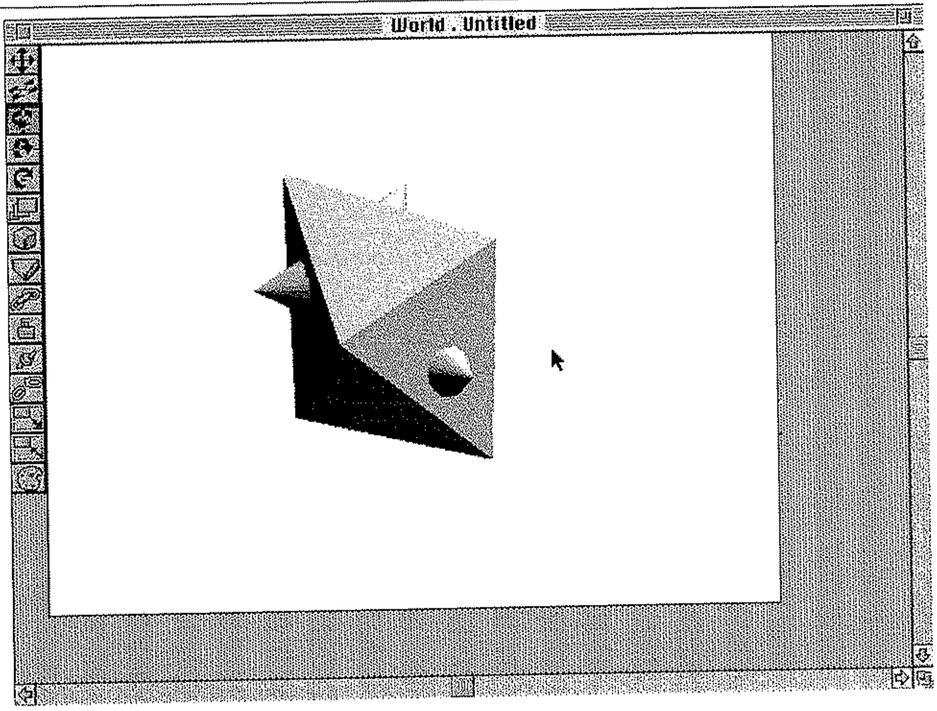


Figure 41 - Abstract object (octahedron with 4 spikes) built in Swivel3D (7 min.)



The surfaces of revolution group contained eight objects that can be created in one surface of revolution: lamppost, bottle, spray-can, lamp-shade, umbrella, barrel, vase and apple.

Figure 42 - Surface of revolution (lampshade) built in IDM/IM (1 min.)

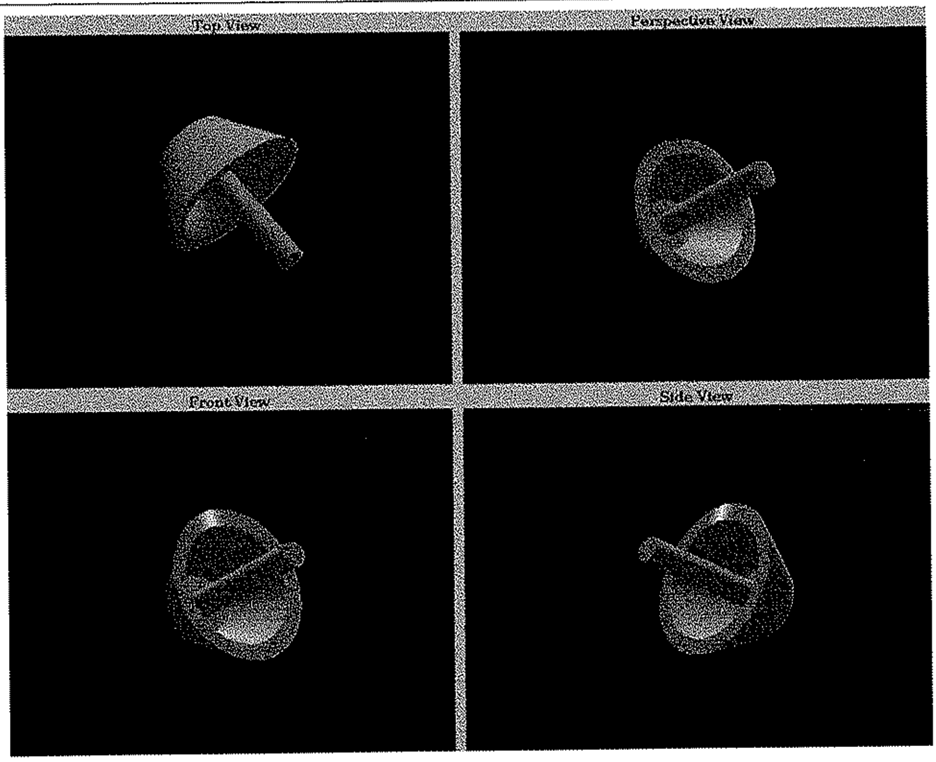


Figure 43 - Surface of revolution (lampshade) built in I3DM (1 min.)

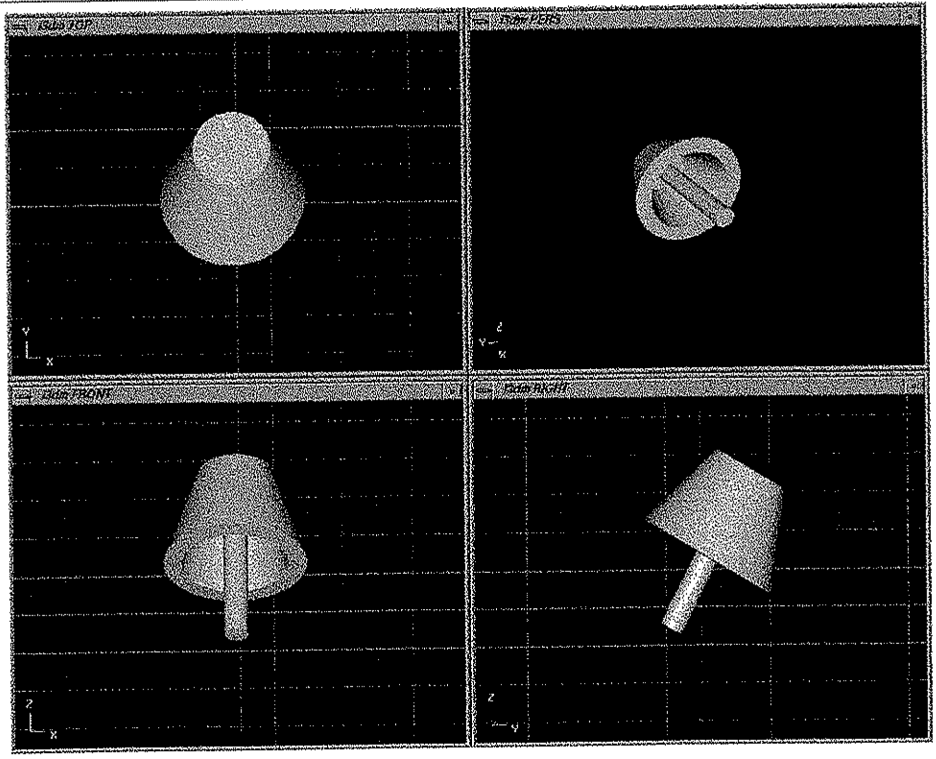
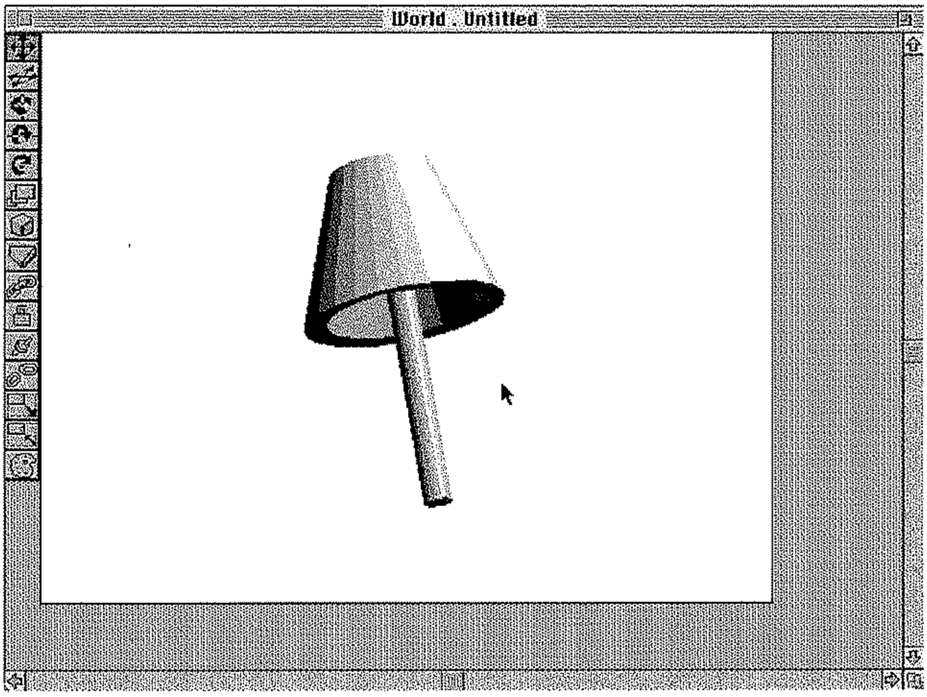


Figure 44 - Surface of revolution (lampshade) built in Swivel3D (1 min.)



The composite group contained eight objects that can be constructed by joining primitive objects: bed with headrest, table, chair, bookshelf, traffic-light, chair without back, lego-brick and luggage.

Figure 45 - Composite object (traffic light) built in IDM/IM (10 min.)

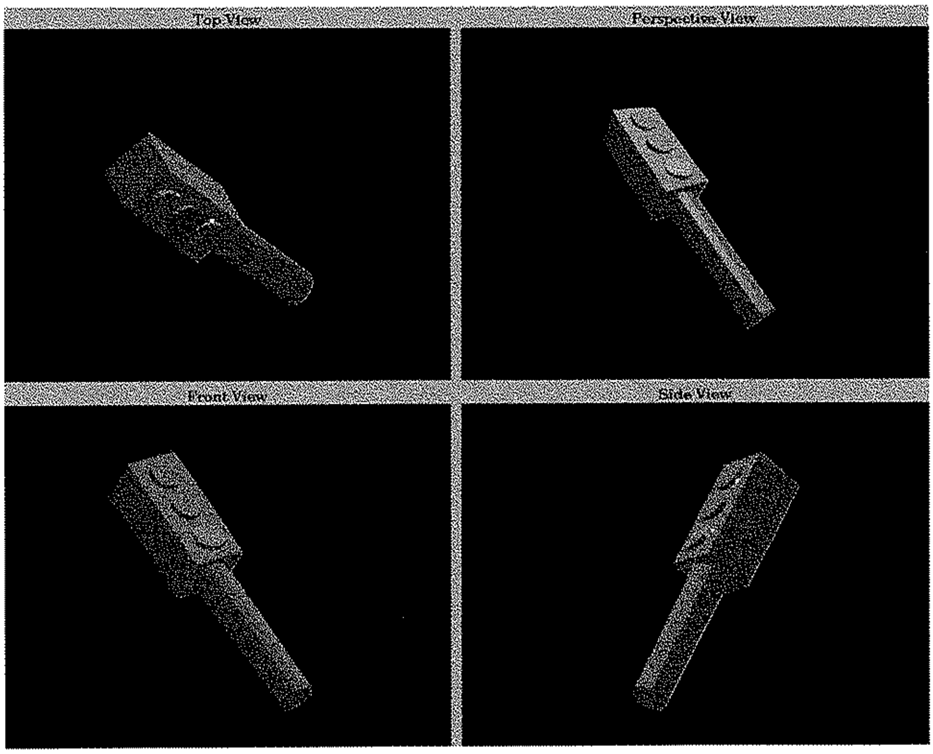


Figure 46 - Composite object (traffic light) built in I3DM (6 min.)

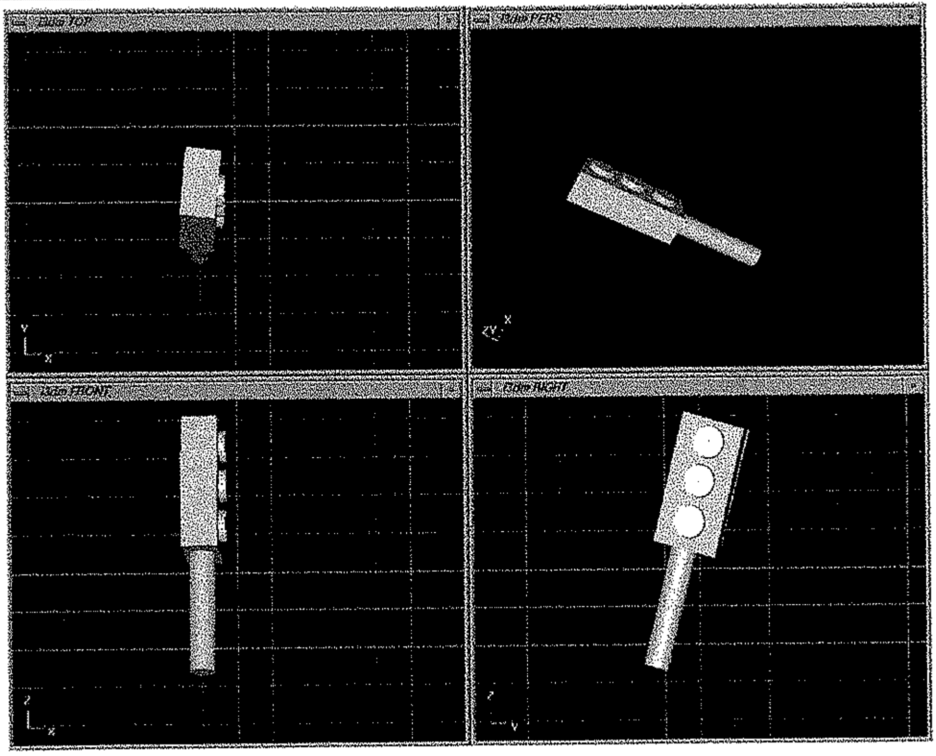
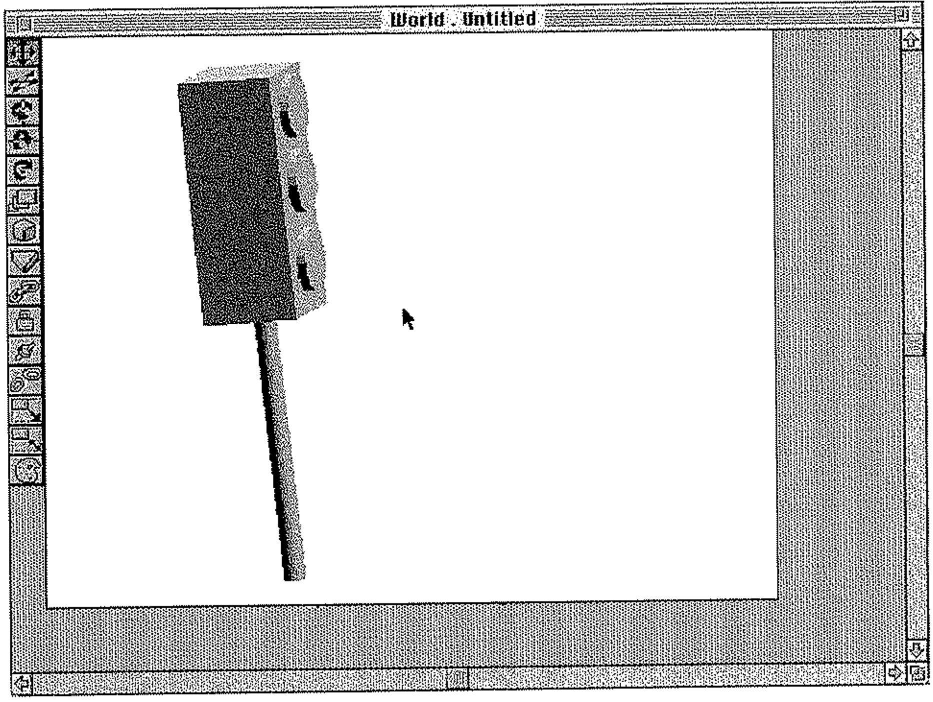


Figure 47 - Composite object (traffic light) built in Swivel3D (6 min.)



And finally the general objects group was formed by eight objects that could be built by the geometrical or the physical method: aeroplane, fish, bird, pineapple, cushion, ship-hull, tulip and dinosaur's back.

Figure 48 - General object (pineapple) built in IDM (8 min.)

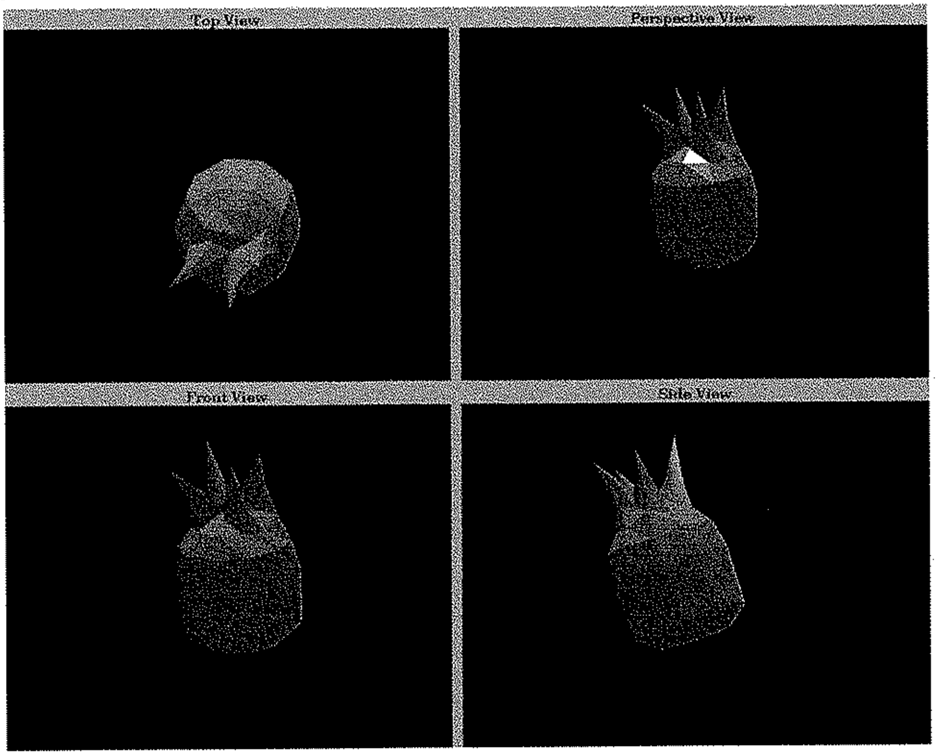


Figure 49 - General object (pineapple) built in IM (3 min.)

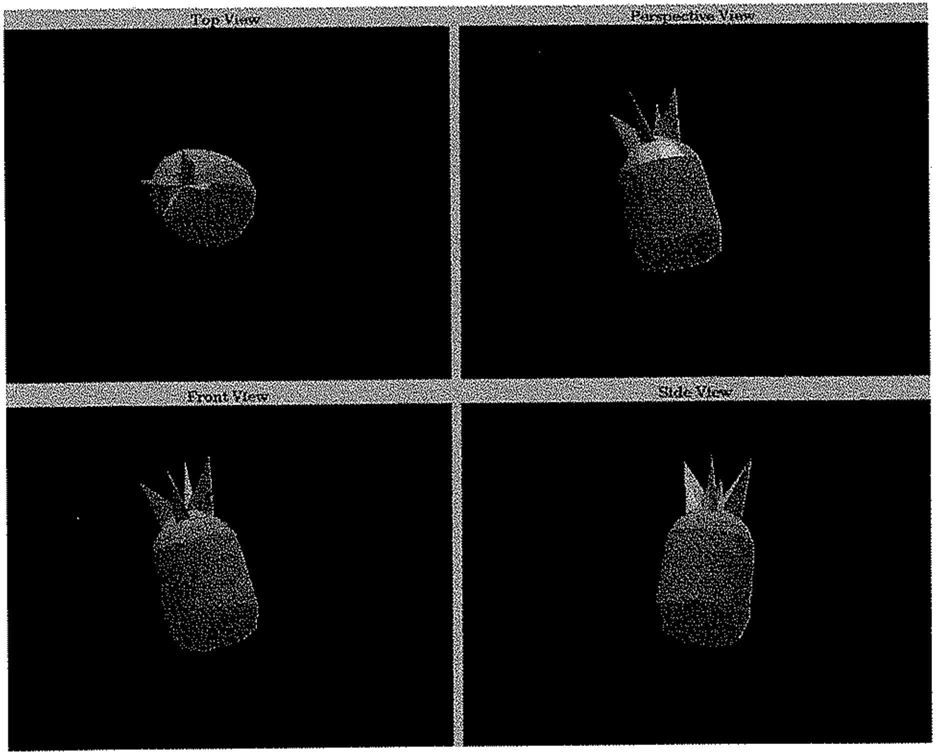


Figure 50 - General object (pineapple) built in I3DM (12 min.)

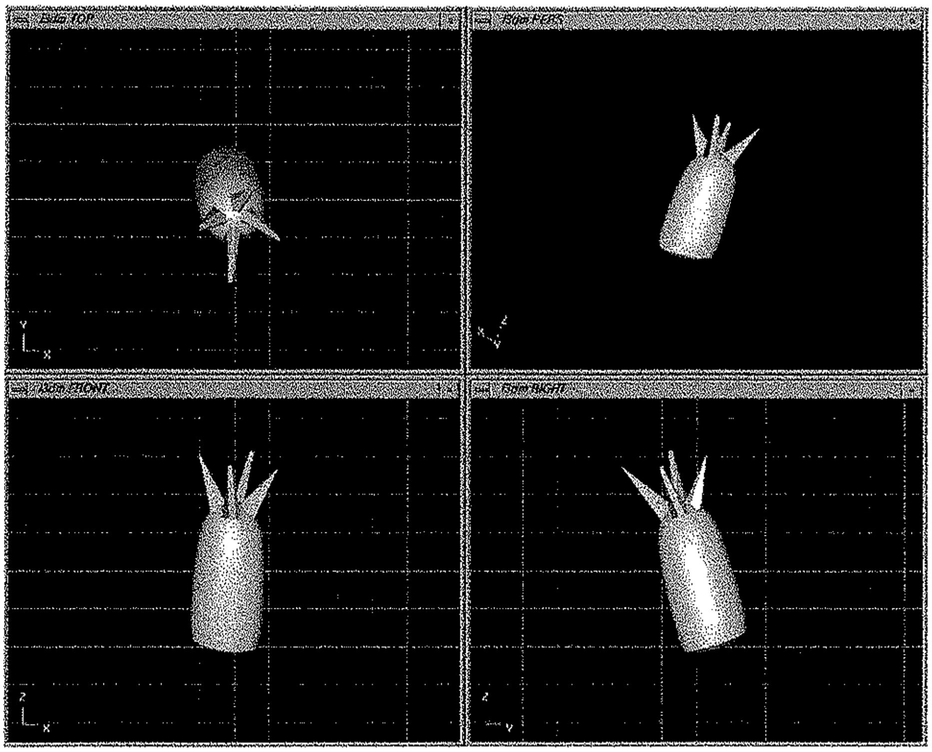
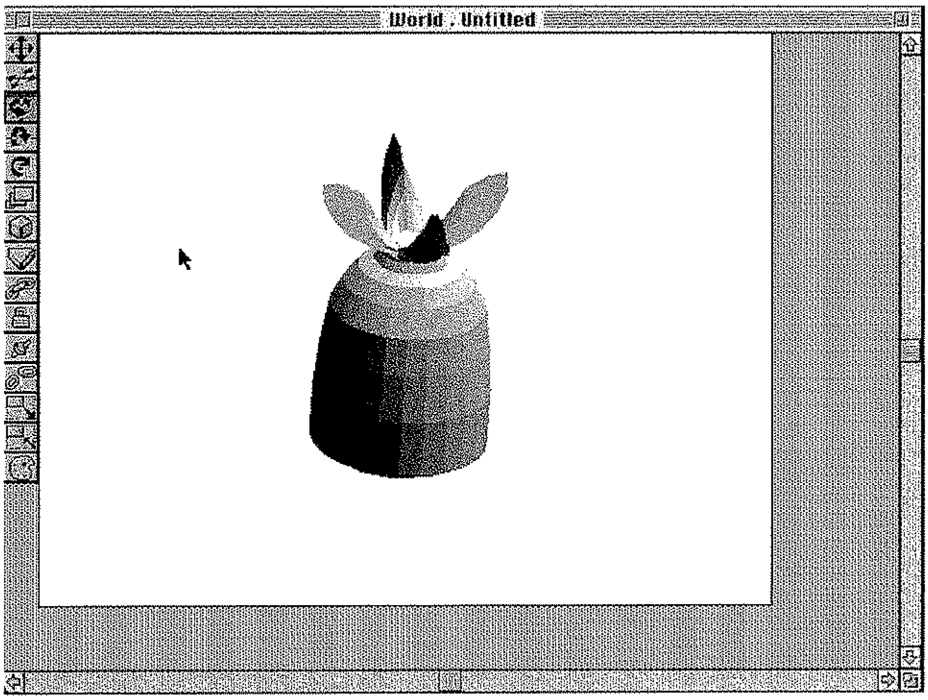


Figure 51 - General object (pineapple) built in Swivel3D (5 min.)



Thus, in total six tasks were performed, where the subject built an object from each group using a given application.

Such tasks served as basis for the measurements which were most relevant to this research:

1. Length of time taken to execute each task;
2. Level of satisfaction by the user about the end result;
3. The location and ease of use of the tools.

Item 1 was achieved by timing all tasks to the nearest second.

Item 2 was measured by collecting answers from a questionnaire given to the subject at the end of each task and also at the end of the whole experiment to test the overall user satisfaction.

Item 3 was measured through a questionnaire given at the end of the whole experiment.

However, apart from the mentioned measurements, others needed to be taken in order to test the hypothesis that there was a spatial ability difference between the two groups used: Arts and Sciences. Therefore measurements of spatial abilities were obtained through a visual/auditory/kinaesthetic questionnaire and a spatial ability test.

5.3 Experimental Design

Now that the methodology and the most relevant measurements were defined, the different elements of this evaluation could be identified and designed. These elements will be presented in a way that coincides with the order in which they were used during the evaluation. Their initial design will be described and followed, when applicable, by the problems encountered as a result of the pilot studies and the solutions to these problems.

5.3.1 Visual/Auditory/Kinaesthetic Questionnaire

The Visual/Auditory/Kinaesthetic (VAK) questionnaire was developed by Slater, Usoh and Steed [54,55] in order to help understand subjects' perceptual preferences. The questionnaire is based on a therapeutic model known as Neuro-Linguistic Programming (NLP). The NLP model claims that a subject experiences reality in terms of three representation systems: visual, auditory and kinaesthetic. "*The Visual system includes external images and remembered and constructed internal images. The Auditory system includes external sounds, and internal remembered and constructed sounds. It also includes internal dialogue, that is the person talking to himself on the inside. The Kinaesthetic system includes tactile sensations, the sensations caused by external forces acting on the body, and also emotional responses (which are reduced to specific patterns* *of internal tactile and haptic sensations). Practitioners of the method claim that people have a tendency to prefer one representation system over the others, at least in a given context*" [54].

For example, in the context of this thesis, when a subject was given a particular object to build s/he might have chosen to mentally visualize its construction, or have an internal dialogue with herself/himself, or recall the tactile sense involved in the manipulation of real clay models.

Therefore the VAK Questionnaire was part of this evaluation in order to establish if there was any relationship between visual representation and the two groups of subjects used (Arts/Sciences) and whether visual preference benefitted performance. A high visual representation meant that the visual representation got the greatest number of 1s when the answers were distributed among the three representation systems (see below).

The VAK questionnaire was comprised of ten questions with three answers each relating to the three representation systems. The subject was then asked to rate the three answers with numbers from 1 to 3 according to what they were most to least likely to do.

Below is the first question extracted from the questionnaire as an example:

1. You are parting from your best friend. Rank the following in order according to what you might say to him/her. (1 = most likely, 3 = least likely).

I might say ...	Rank each answer: 1 = most likely, 2 = next most likely, 3 = least likely
"Let's talk again soon."	
"Let's see each other again soon."	
"Let's do something together again soon."	

For more details please refer to Appendix V on page 155.

This questionnaire was successfully used as the basis of the prediction of presence in Virtual Reality [54,55].

5.3.2 Spatial Ability Test

As with the VAK questionnaire, a spatial ability test was used in order to test the hypothesis that there was a relationship between a subject's spatial ability and the group it belonged (Arts/Sciences). This test was also used in the analysis of the tasks performed.

The spatial ability test chosen was one of the tests belonging to the General Ability Tests (GAT) [45]. The GAT is actually comprised of four tests: a verbal, a non-verbal, a numerical and a spatial but all tests can be administered together or independently because there isn't a battery or total score.

The spatial test requires *"the test taker to mentally envision a three-dimensional shape that could be made from a cut and folded two-dimensional drawing. Perspective drawings of various objects are presented, and the test taker must indicate which are possible representations of the two-dimensional form as manipulated. The user's guide states that this form of test is similar to the General Aptitude Test Battery (GATB)* [25] *3-D Space and other spatial tests that have proven useful in predicting occupational success in engineering, construction, and other jobs requiring spatial imagination. Unlike other spatial tests, however, the Spatial Test includes varied shapes. In contrast, many such tests focus on cubes and rectangles. Because more different types of shapes and irregular shapes are included, the difficulty level of the Spatial Test is probably higher than that of other such tests. The Spatial Test requires 20 minutes for administration, after approximately 10 minutes of instructions."* [35]. In total twenty objects are presented as "unfolded" 2D drawings. Each object has four perspective drawings of various "folded" 3D objects. The test taker then must indicate if each "folded" 3D drawing is a possible representation of the "unfolded" 2D drawing ((Y)es or (N)o answer). Twenty objects with four 'yes' or 'no' answers make a maximum score of 80 points.

Therefore when a high spatial ability is referred to in this work it means a high score in this particular spatial ability test meaning a high ability to manipulate unfolded 2D patterns. Of course one could expect that a high score would correlate with the everyday meaning attributed to "spatial ability".

Unfortunately because of copyright laws the author cannot attach a copy of the test so the reader is asked to contact the suppliers [45] for more details.

5.3.3 Introduction Sheet

To facilitate the subject's understanding of the whole experiment an introduction sheet was produced which explained what was involved in the experiments and how they would be conducted, with a step by step description of the procedures to follow.

Appendix III on page 130 shows its final design.

5.3.4 Questionnaire 1 - Background

Questionnaires 1, 2 and 3 (which will be described later) went through many design cycles, which were needed to eliminate ambiguity and misunderstanding of questions or answers.

Furthermore where rating scales were used the "split ballot" technique [48] was applied in order to minimise bias answers. As shown by [48] the way an answer is presented to the interviewee influences his/her answer, i.e. if negative answers are presented before positive answers the data collected will be different from presenting them in reverse order. To avoid this problem the "split ballot" technique divides the sample into two groups where one group is given a questionnaire with the negative answers first and the other with positive answers first, designated in this work by the letters A and B after the questionnaire number. This way if any discrepancies occurred these were minimised.

Questionnaire 1 then collected a subject's background information: gender, handedness, education, previous technical drawing experience, up to five hobbies, previous experience with the application to be used, previous experience with CAD applications, previous machine experience, that is if a subject used the particular machine s/he was given to work on, and computer experience, that is how often a subject used a computer.

Appendix V on page 159 shows Questionnaire 1's final design.

5.3.5 Learning Process

In order to complete the required tasks the subject first needed to learn how the application worked and what tools it had. So a specified amount of time was given to the subject in order to allow him/her to explore the application and its tools through its help facilities. To make sure the subject would have the knowledge of the tools needed to achieve the tasks, some recommendations were made as to which activities he/she should learn: how to create an object, how to create surfaces of revolution, how to duplicate objects and how to group/connect two objects.

However, after the first set of pilot studies some major problems arose:

1. *Help didn't get read;*
2. *Not all recommended learning points were achieved (mainly surfaces of revolution);*
3. *The meanings of "extrude" and "surfaces of revolution" were not clear.*

As a consequence the knowledge across subjects was not leveled and the basic knowledge necessary for the execution of the tasks was not achieved.

These problems were overcome by a tutorial designed for each of the applications which forced the subject to learn all the necessary tools to execute the tasks and level knowledge across subjects. The tutorial had steps which were followed by the subjects showing him/ her in detail how the tools worked and their functionality together with an explanation and examples of the terms "extrusion" and "surfaces of revolution".

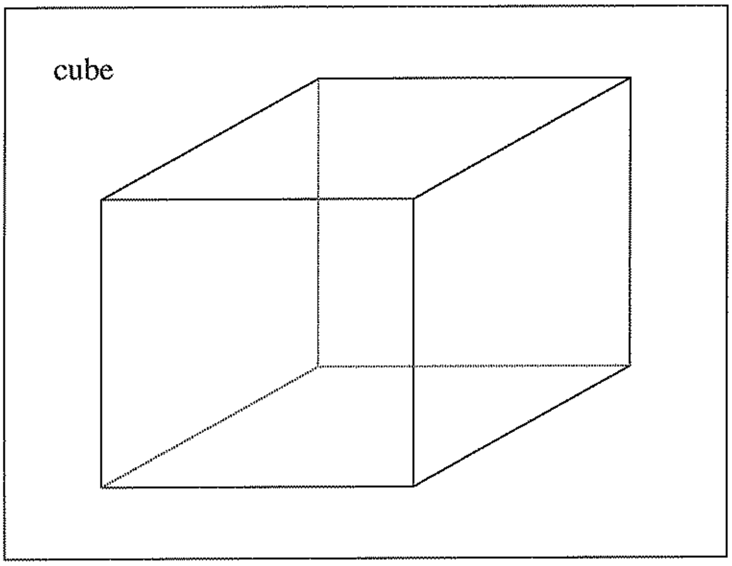
Appendix IV on page 131 shows the final design of the tutorial for each of the applications.

5.3.6 Object Distribution and Presentation

The next step was to define which object from a group to give to the subject and how this object would be presented to him/her.

It was first decided that each group of objects should have a set of hard paper cards, one for each of its objects, with the name and a 2D drawing of the object printed on it. This set of cards was then presented face down to the subject who picked one of them. The chosen card was then turned face up revealing the chosen object's characteristics. Figure 52 shows one of such cards in its original size as an example. Appendix I on page 126 shows in reduced size the cards related to the other objects.

Figure 52 - Object card



The subject was then asked to build the chosen object using a given application.

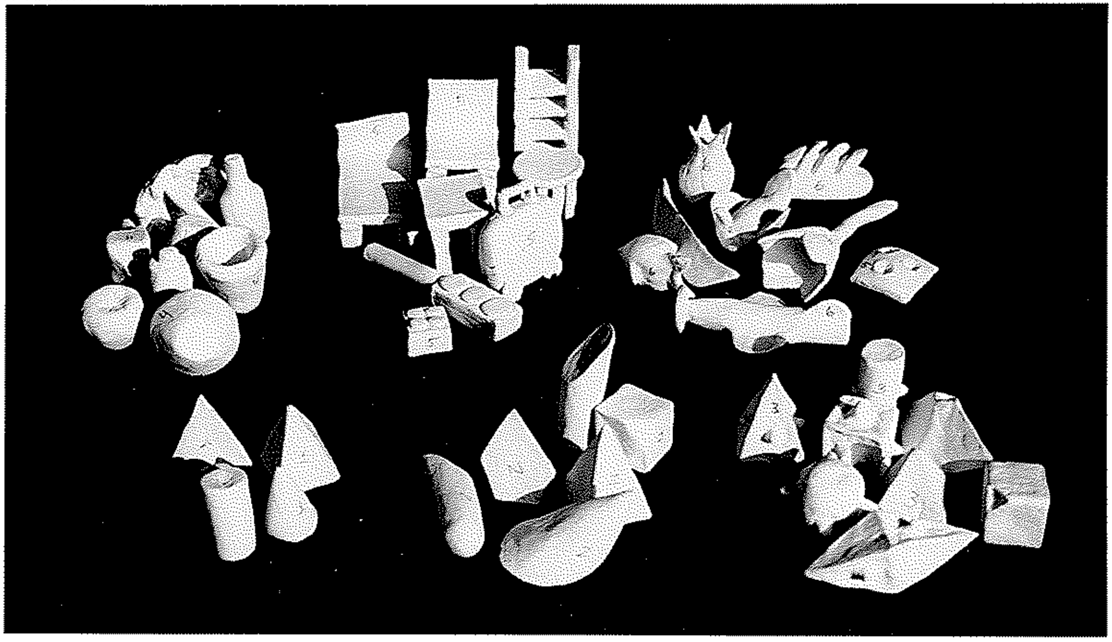
However, after the first pilot study one major problem was identified:

- *There were too many interpretations for the objects, that is some subjects saw them as 3D solid objects but others as 3D objects made of faces, made of lines but not forming a face, made just of edges (wireframe) or tried to draw the 2D sketch as seen in the hard paper card.*

In order to solve this problem a small clay model of each object was made to substitute its drawn representation. Although the paper cards were kept as a way of randomly selecting which object would be given to the subject, they contained just the name of the object without its drawing.

Figure 53 below shows all the objects made from white modelling clay.

Figure 53 - Modelling clay objects



5.3.7 Questionnaire 2 - About Each Task Performed

Questionnaire 2's main objective was to provide the research with a user's self assessment about his/her level of satisfaction and overall level of difficulty with each of the tasks after each of them was performed.

However, after the pilot studies, other measurements were identified and added to the design: before actually building the object the subject was asked to describe in no more than four statements how s/he intended to create the object so providing data on the way the subject thought about the task beforehand; after the task, and in addition to the level of satisfaction and overall level of difficulty mentioned previously, the subject was asked to describe the task's most difficult aspect and rate its level of difficulty.

Appendix V on page 162 shows Questionnaire 2's final design.

5.3.8 Questionnaire 3 - About the Whole Experiment

Once all the six tasks were completed the user was given Questionnaire 3 which collected information on the following:

- level of satisfaction with all tasks performed;
- level of satisfaction with the application used;
- how easy it was to locate the tools needed;
- how easy it was to use the tools needed;
- the most useful feature and why;
- the least useful feature and why;
- the description of any additional tool the subject would like to have for any of the tasks;
- any suggestions or comments about the application used
- and any comments or suggestions about the experiment itself.

In addition, a list of 19 words was given and the subject was asked to tick five of them which most reminded him/her of the application used. This data was collected with the intent of evaluate the user's mental model. The words were: adapting, altering, constructing, designing, manufacturing, outlining, sketching, engraving, assembling, copying, drawing, merging, painting, tracing, adjusting, building, crafting, modelling and sculpting.

Appendix V on page 176 shows Questionnaire 3's final design.

5.3.9 Observer's Sheet

In order to record information such as timings and comments about the tasks from the researcher's point of view an observer's sheet was also designed. It contained the times taken to execute the whole experiment, the tutorial, to think about each of the tasks, to execute each of the tasks, a set of options to indicate if the subject used the forces, moving vertices, connected the objects, use revolution, built object as just one, the final number of objects and general comments about the task.

Appendix VI on page 181 shows its final design.

5.3.10 Additional Design Implications after Pilot Studies

Apart from the changes already described in previous sections as a consequence of problems identified during the pilot studies, one last problem remained to be described:

- *Subjects exhibited great difficulty in coping with just one camera in the developed application (both versions), especially because the camera showed the object in perspective view.*

This called for a major redesign of the developed application interface including a change in hardware platform. The application needed to have at least three views of the scene: front, top and side. Such a change would affect its performance since instead of rendering the image only once, at least three times that amount was necessary. This required a graphical hardware improvement, thus the change from a Sun workstation to a Silicon Graphics machine. For aesthetic reasons, dividing the screen into four areas would look better than three, so the perspective view was kept and the other three views were added.

Now that the reader is familiar with all the elements in this evaluation a description of how the experiments were conducted can be presented.

5.4 Procedures

Experiments were conducted using 40 subjects representing two groups: an expected high and low degree of spatial ability, namely arts and sciences students. Each group of 20 subjects was further sub-divided into four sub-groups in order to test the three geometrically based applications and the physically based one (Table 6).

Table 6 - Subject distribution

Subject distribution	**Arts**	**Sciences**
IDM (author's physical application)	5	5
IM (author's geometrical app.)	5	5
I3DM	5	5
Swivel3D	5	5
Total	20	20

When recruiting the subject s/he was given the VAK questionnaire described in Section 5.3.1 and asked to take part in the first session of the experiments. When coming to the first part the subject was given a number and this number identified him/her throughout the whole experiment and also defined which application s/he was going to use. The first session consisted of the spatial ability test which, as explained in Section 5.3.2, had a practice session lasting around ten minutes and the test itself which lasted no more than 20 minutes. The subject also handed in the VAK questionnaire and was asked to come to the second part of the experiment to be held another day.

When coming for the second session the subject was first sat in front of the machine s/he was going to work with and be presented with the respective application. The introduction sheet described in Section 5.3.3 was given followed by Questionnaire 1 (Section 5.3.4). Once finished, the subject was given time to go through the tutorial (Section 5.3.5) relative to the application in use. Meanwhile the researcher started to time the tutorial and sat next to the subject, first to make sure s/he was following all the written instructions and second to answer any queries that might arise. Once the tutorial was completed (which took on average 40 minutes) the researcher stopped the timing, verbally explained to the subject what tasks were going to follow and gave him/her Questionnaire 2 (Section 5.3.7). Once understood, each task was given to the subject, one at the time, and the same procedure was followed for each of them. First a set of cards, face down, was presented to the subject so that s/he could pick one of them and return to the researcher, face down, who went and picked up the corresponding clay model (Section 5.3.6). The researcher then stated what the object was, gave the model to the subject, asked him/her first "to answer in no more than four statements how you intend to build this object in the computer" and timed the written answer. Once finished, the subject was allowed to start building the object using the designated application while being timed and observed by the researcher.

The observations and timings were noted in the observer's sheet as described in Section 5.3.9.

Once the object was completed the subject was given time to answer questions relating to the resulting object, as shown in Appendix V on page 162, Questionnaire 2, questions 2 to 5 and alike.

This procedure was repeated for all six tasks and was followed by Questionnaire 3 (Section 5.3.8).

On average the whole experiment took two and half hours and although quite demanding it received a majority of positive comments: *"very interesting and fun"*, *"it was enjoyable and interesting"*, *"fun to do"*, *"it was conducted in a pleasant and relaxed manner"*, *"I didn't get bored"*, *"I enjoyed the experience"*.

5.5 Summary

This chapter presented the design and implementation of the whole evaluation process. It started with the experimental method then moved on to describe the elements of this evaluation: the VAK questionnaire, the spatial ability test, the introduction sheet, Questionnaire 1 (background), the tutorial, the objects' representation, Questionnaire 2 (about each task performed), Questionnaire 3 (about the whole experiment) and the observer's sheet. And finally the description of how the experiments were conducted was presented.

The next chapter presents an analysis of the results based on the data collected.

Chapter 6 Results

6.1 Introduction

An informal analysis of the data was carried out using basic frequency and raw tabulation data. A more sophisticated analysis involved the use of linear regression.

The linear regression analysis is a statistical method which attempts to explain variations in dependent variables and as it forms the basis of the analysis described in this chapter it is presented first.

This description is followed by a description of the strategy of use; the general characteristics of the subjects based on the raw data; the analysis on the spatial ability test score between the Arts and Sciences groups as it was believed that there would be a difference; the results obtained from the analysis amongst the geometrical applications and the results obtained from the analysis between the geometrical and the physical methods. Finally, the methodology itself is discussed and suggestions are made for improvements to the protocol described in Appendix II on page 128 in the light of the results of the research.

6.2 Linear Regression Analysis

6.2.1 Introduction

Regression analysis [14,44], in general terms, means the analysis of relationships amongst variables. This relationship is represented in the form of an equation, the regression equation, which takes the linear form

$$y = \beta_0 + \beta_1 x_1 + \beta_2 x_2 + \ldots + \beta_n x_n + \varepsilon \qquad (52)$$

where y is the dependent variable, $\beta_0, \beta_1, \ldots, \beta_n$ are the regression coefficients and are calculated from the data, $x_1, x_2, \ldots, x_n$ are the independent variables and ε is a normally distributed random variable with zero mean and variance constant for all observations.

As this work is interested in the interpretation of the final product, that is, the regression equation itself, the reader is asked to refer to [14,44] for an explanation of how the regression coefficients $\beta_0, \beta_1, \ldots, \beta_n$ are calculated.

These coefficients then define the positive or negative relationship between the dependent variable y and the respective independent variable $x_1, x_2, \ldots, x_n$. For example, in the context of this thesis if we had a regression equation such as

$$\text{spatial ability score} = 3.67 + 2.5\ \text{age} - 5.3\ \text{computer experience} \tag{53}$$

It would mean that other things being equal the older the subject the higher the spatial ability score (positive relationship) but the computer expert would have a low score compared to a novice (negative relationship).

Positive and negative relationships are used when the variables are measured in a scale form, such as age or computer experience (scale from 1 to 7), but when there are a specific number of answers involved, such as sex or previous technical drawing experience (yes/no), there will be a number of regression equations to match the number of answers. For example,

$$\begin{aligned} \text{spatial ability score} &= 3.67 + 2.5\ \text{sex(female)} \\ \text{spatial ability score} &= 3.67 + 1.5\ \text{sex(male)} \end{aligned} \tag{54}$$

In order to interpret them correctly one looks at the coefficients for the variable (sex) where the highest one indicates a positive relationship against the other, that is to say in the example given that, other things being equal, a female would have a higher spatial ability score than a male.

These positive/negative and scale form relationships will be used in table form with the appropriate interpretation when presenting the results from the analysis amongst applications and also from the analysis between methods.

All the linear regression equations used in the analysis to follow were produced using the Generalised Linear Interactive Modelling system (GLIM) [26] and are presented in table form in Appendix VIII on page 188 for the analysis amongst applications and in Appendix IX on page 207 for the analysis between methods.

6.2.2 Strategy of Use

There were two ways in which the linear regression was used in this work.

The first was an attempt to explain the variation in a number of independent variables while controlling for the crucial independent variable describing the application used. This was done through a process called 'stepwise regression' whereby first the variable which represented the application was fitted to the regression equation and kept as a variable in the model. Other dependent variables were then added one by one to the same regression equation. If the added variable increased significantly the correlation between the application variable and the independent variable being measured then the added variable was kept in the model otherwise it was taken out (Table 16 to Table 30 on page 190 for the analysis of the geometrical applications and Table 53 to Table 58 on page 209 for the analysis of the methods). Where the results were significant this analysis served the purpose of examining the influence of the applications onto the independent variable which was being explained.

The second way was an attempt to fit a model, or a set of characteristics per application which correlated to the three sets mentioned: satisfaction, use of tools and timings per task. As in first analysis the 'stepwise regression' was used but instead of keeping the added variables which significantly increased the correlation between the independent variable and the application variable, the added variable which caused the greatest increase in correlation between the independent variable and the whole regression equation was kept (Table 31 to Table 52 on page 193 for the analysis of the geometrical applications and Table 59 to Table 80 on page 210 for the analysis of the methods). The purpose was to examine the differences in the relation between the independent variables and the explanatory variables across the applications. In total twenty two models were fitted for the user interface analysis and an equal number for the analysis of the methods. No direct statement, such as 'X is better than Y', can be extracted from these models but some significant correlations were found. These can be used to build a user profile for a particular task or application.

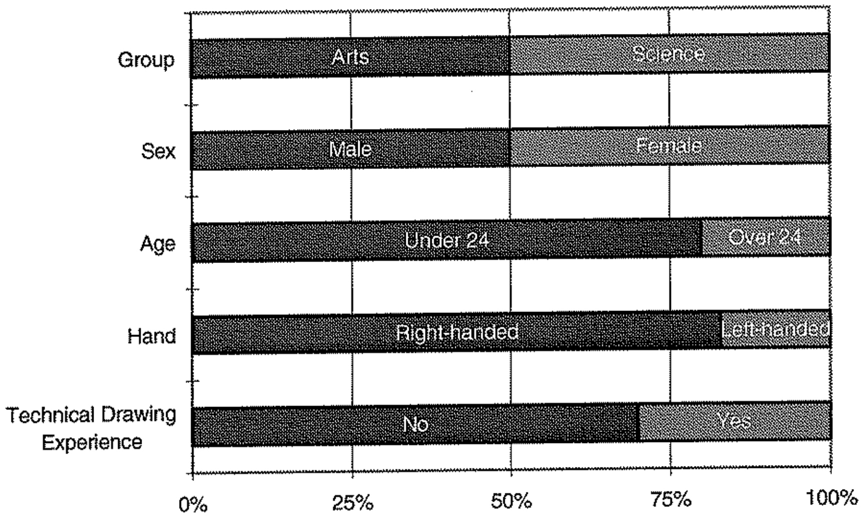
6.3 Subjects' General Characteristics

In total, 45 subjects took part in the experiment of which 40 completed the whole experiment and 5 did just the first part (the spatial ability test). Thus for the spatial ability score analysis, to be presented in the next section, all 45 subjects were entered but for the main analysis, including the characteristics presented here, just the 40 who completed the experiment are taken into account.

All the subjects used were students where half were reading Arts and the other half reading sciences. 50% were female and 50% male, 80% were under the age of 24, 17% were left-handed, 30% had some technical drawing experience, and 17% had used a CAD related application. Figure 54 shows these characteristics in graph form.

For a more detailed description please refer to Appendix VII on page 184.

Figure 54 - Subjects' General Characteristics



6.4 General Frequencies

Apart from the frequency of variables per application there were some variables which can be described in terms of the whole sample. 63% of those who used the Silicon Graphics machine had problems with the mouse; when all the answers for the VAK questionnaire were classified by visual, auditory and kinaesthetic, that is how many 1s each one received, it resulted in an equal number amongst them; the four most associated words with the applications were: constructing, designing, assembling and building; from the subjects who used I3DM and Swivel3D, which did not have a cutting tool, just 45% of them actually suggested it as an additional tool in Questionnaire 3; 27% of subjects asked for a better tool for joining/grouping objects and 52% had something positive to say when commenting on the application.

For a more detailed description please refer to Appendix VII on page 184.

6.5 Comparing Spatial Ability Scores

An earlier belief was that Arts students would have a lower spatial ability score than Sciences students. However, both analyses, the raw data and the linear regression, showed that there was no significant difference between the groups with respect to spatial ability score.

The mean (average) score for the Arts group was 65 against 67 for Sciences where the maximum possible score is 80. If the scores for the people who didn't complete the experiments were also included this difference decreased to 64 from Arts against 65 from Sciences.

The linear regression analysis also showed no significant correlation between score and age, sex, hand, previous technical drawing experience, CAD experience, computer experience or Visual/Auditory/Kinaesthetic (VAK) questionnaire per group.

6.6 User Interface Analysis

The first analysis involved three of the four applications used: Interactive Modeller (IM) which was developed by this work as a geometrical application, Interactive 3D Modeler (I3DM) and Swivel3D.

For the purpose of comparison three separate indicators were considered: level of satisfaction, use of tools and time. The level of satisfaction included the satisfaction with each task performed, with the application and with the work as a whole (all tasks). The use of tools included how easy it was for the user to locate and to use the tools available. Time was the time taken for the user to think about how to execute each task and the time taken to actually execute them. The time to think about an object was the time from when the user was given the real clay model until s/he finished describing in no more than four steps how s/he intended to build the object.

Note that, on the linear regression analysis, 'level of satisfaction' was measured on an ordinal scale and is therefore not strictly suitable as a variable on the left hand side of a regression equation. It was used in this way however in a spirit of data exploration rather than formal hypothesis testing.

6.6.1 Raw Data Results

Table 7 shows the first set of data, satisfaction, with the percentage of subjects which selected the two upper levels from a satisfaction scale of 1 to 7.

Table 7 - % of People with Levels 6 and 7 of Satisfaction with applications

Level of Satisfaction	IM (%)	I3DM (%)	Swivel3D (%)
Task 1 - primitive	70	60	70
Task 2 - primitive with cut	50	10	0
Task 3 - abstract	60	50	40
Task 4 - revolution	90	60	70
Task 5 - composite	50	50	70
Task 6 - general	40	20	40
All tasks combined	60	41	48
application	80	50	80
Work	50	40	40

The first six rows show the level of satisfaction with each of the tasks (self evaluation from user). For a more detailed description of the tasks please refer back to "Experimental Method" on page 73. The next row (All tasks combined) is the result of adding the number of subjects which selected levels 6 or 7 for each of the tasks then calculating the percentage. The last two rows show the percentage of subjects who selected levels 6 or 7 when self evaluating the level of satisfaction with the application and the level of satisfaction with the overall work performed after doing all tasks.

Those results indicate that subjects were more satisfied with IM (greater percentage compared to the other two applications) or as satisfied with IM (same percentage) as with the other two applications.

The next table (Table 8) shows the results of the use of tools which each application had available to the user to perform his/her task.

Table 8 - % of People with Levels 6 and 7 for Easy to Use Tools

Use of Tools	IM (%)	I3DM (%)	Swivel3D (%)
Easy to locate	80	20	50
Easy to use	60	30	20

This indicates that the subjects found the IM tools easier to locate and use than the other two applications.

The time to execute each of the tasks is presented in two ways: one using just half of the data and the other using the whole data set. Table 9 shows the percentage attributed to each application from the fastest half of the data, that is, the data set was divided into two groups, lower half or fastest, and upper half or slowest, and the percentage shows how many subjects were in that set of data from each application. For example, from the fastest times taken to build the primitive object, 40% were IM subjects, 27% were I3DM and 33% were Swivel3D subjects.

Table 9 - % of Subjects which Fell in the Fastest Half of Times to Execute each Task

Fastest Half Times	IM (%)	I3DM (%)	Swivel3D (%)
Build primitive object	40	27	33
Build cut object	46	27	27
Build abstract object	60	27	13
Build revolution object	46	27	27
Build composite object	27	40	33
Build general object	53	27	20
All objects combined	46	29	25

These times however indicates that in IM the subjects performed the tasks faster than the other two applications in all but in the construction of the composite object.

The following table shows the mean and standard deviation for times taken to execute each of the tasks.

Table 10 - Means and Standard Deviations for Times Taken to Execute Each Tasks

	IM	I3DM	Swivel3D
Build primitive object	187 ± 156	325 ± 300	239 ± 192
Build cut object	550 ± 443	702 ± 417	934 ± 433
Build abstract object	495 ± 301	839 ± 208	983 ± 258
Build revolution object	154 ± 122	180 ± 117	211 ± 132
Build composite object	865 ± 379	846 ± 292	913 ± 345
Build general object	630 ± 314	871 ± 315	911 ± 295
All objects combined	480 ± 136	627 ± 135	698 ± 160

Table 10 still shows that the subject performs all the tasks, but for the composite object, faster in IM.

In addition, the analysis of variance [44] showed that the differences in means amongst applications were significant for the abstract object ($F(2, 27) = 9.41$, tabulated value at

5% level $F(2, 27) = 3.354$) and for all the objects combined ($F(2, 177) = 4.5$, tabulated value at 5% level $F(2, 177) = 3$).

For the mean and standard deviation of other variables please refer to Appendix VII on page 184

6.6.2 Linear Regression Results

These are the significant correlations (at the tabulated 5% level) found when attempting to explain some dependent variables based on application:

- Table 16 on page 190 shows the first regression model (for an index of variable names please refer to page 188):

  Table 16 - Regression of satisfaction with the resulting cut object (t2sa)

	estimate	s.e.	parameter
1	4.739	0.6624	CONSTANT
2	1.166	0.6731	PKG(2)
3	-0.6898	0.6832	PKG(3)
4	-0.002193	0.0006644	T2

  As explained in Section 6.2 on page 95 three regression equations, one for each application, are produced. Let y be the level of satisfaction with the resulting cut object. The three regression equations then are:

Application	Equation
I3DM	$y = 4.74 - 0.0022T2$
IM	$y = (4.74 + 1.16) - 0.0022T2$
Swivel3D	$y = (4.74 - \mathit{0.69}) - 0.0022T2$

  I3DM has a coefficient of 0 because it does not appear in the regression model and Swivel3D coefficient is in italics because it is not significant. IM on the other hand has a significant coefficient. Therefore when comparing the coefficients of these three equations we can state that IM produced the greatest level of satisfaction with the cut object even when the effects of the execution times were taken into account, that is, included in the regression model.

- Swivel3D was faster than the other two applications (IM and I3DM) in the execution times for the primitive object when the effects of thinking time and age were taken into account. The same model also showed that an older subject was quicker at building the primitive object in IM than in I3DM or Swivel3D (Table 17 on page 190).

- Swivel3D was the slowest in the execution times for the cut object when the effects of thinking time and spatial ability scores were taken into account (Table 18 on page 190).
- Swivel3D was the slowest in the thinking time for the abstract object when the effects of age and previous machine use were taken into account (Table 19 on page 191).
- IM was the fastest in the execution times for the abstract object even when the effects of technical drawing experience and computer expertise were taken into account (Table 20 on page 191).
- IM was the fastest in the overall time for the execution of all tasks when the effects of thinking time and spatial ability score were taken into account (Table 21 on page 191).

These show that where the results were significant IM was in general better than the other two.

Other correlations with the applications were found at the tabulated 10% level:

- IM produced the greatest level of satisfaction for the revolution object when the effects of thinking time were taken into account (Table 22 on page 191).
- IM produced the greatest level of satisfaction for all the tasks combined when the effects of subject's self evaluation of satisfaction with the work and thinking time were taken into account. The same model also showed that user's self evaluation of satisfaction with the work was positively and significantly associated with the level of satisfaction with all the tasks combined (Table 23 on page 192). This is important in the sense that it shows the veracity of the data collected.
- IM was the slowest in the thinking time for the revolution object when the effects of spatial ability score were taken into account (Table 24 on page 192).
- IM was the fastest in the execution times for the general object (Table 25 on page 192).

These results, apart from showing the consistency amongst the data, indicated that again IM was in general better than the other two.

Other significant correlations (at the tabulated 5% level), independently of application, were found and convey some extra information:

- Subjects with technical drawing experience were faster at executing the revolution object when the effect of the spatial ability score was taken into account and faster at executing the composite object when the effects of the group was taken into account (Table 26 on page 192).
- Execution times for the tasks were associated in four instances with the level of satisfaction with the tasks. The less time a subject spent executing the primitive, cut, composite or general object the more satisfied s/he was with its final result provided: the effect of the number of auditory answers was taken into account in the primitive object; the effect of application was taken into account in the cut object; and the effect of thinking time was taken into account in the general object. (Table 28 on page 193, Table 16 on page 190, Table 29 on page 193 and Table 30 on page 193).

Apart from the results of the linear regression so far described, a number of models, or set of characteristics were fitted to each variable including user satisfaction, ease of use and timings.

Twenty two models were fitted but instead of presenting each individual one here, a general table was preferred by the author. The twenty two tables however are described and interpreted accordingly in Appendix X on page 220 since these characteristics per task can be used in future work.

For the data in statistical form please refer to Appendix VIII on page 188.

The general table consists of the most predominant occurrence of each variable per application.

For an explanation of positive and negative relationships and the scales such as ‘yes’ or ‘no’ with relation to a dependent variable please refer back to Section 6.2 on page 95.

Table 11 - Resulting General Table

	IM	I3DM	Swivel3D
Age		-	+
Sex	Male	Female	Female
Group (arts/sciences)	Arts		Arts
Previous technical drawing experience	No	Yes	Yes
Computer experience	+	+	-
Previous CAD experience	Yes	No	Yes
Spatial ability score	-		
Number of visual answers in VAK quest.	+	+	-
Number of auditory answers in VAK quest	+	-	-
Time spent on tutorial	+	-	

Table 11 shows that the best subject for IM was a male, doing an arts related subject, with no previous technical drawing experience but with computer and previous CAD experience, who had a low score in the spatial ability test but a high number of visual and auditory answers in the VAK questionnaire, and finally, spent more time doing the tutorial.

Similarly the best subject for I3DM was a younger female, with previous technical drawing experience and computer experience but no previous CAD experience, who had a high number of visual but a low number of auditory answers in the VAK questionnaire, and finally, spent less time doing the tutorial.

In the case of Swivel3D the best subject was an older female doing an arts related subject, with previous technical drawing and CAD experience but with less computer experience, and, with a low number of visual and auditory answers in the VAK questionnaire.

6.7 Analysis of the Methods

This second analysis involved the two applications developed in this work: Interactive Deformable Model (IDM) representing the physical method, and Interactive Modeller (IM) representing the geometrical method.

As for the first comparison the same three separate indicators were considered: level of satisfaction, use of tools and time.

6.7.1 Raw Data Results

Table 12 shows the first set of data, satisfaction, with the percentage of subjects which selected the two upper levels from a satisfaction scale of 1 to 7. For a more detailed description of the tasks please refer back to "Experimental Method" on page 73.

Table 12 - % of People with Levels 6 and 7 of Satisfaction with applications

Level of Satisfaction	IDM (%)	IM (%)
Task 1 - primitive	70	70
Task 2 - primitive with cut	60	50
Task 3 - abstract	20	60
Task 4 - revolution	40	90
Task 5 - composite	20	50
Task 6 - general	20	40
All tasks combined	38	60
application	60	80
Work	30	50

The above results indicate that subjects were more satisfied with IM (geometrical) than with IDM (physical).

The time to execute each of the tasks is presented in two ways: one using just half of the data and the other using the whole data set. Table 13 shows the percentage attributed to each application from the fastest half of the data, that is, the data set was divided into two groups, lower half or fastest, and upper half or slowest, and the percentage shows how many subjects were in that set of data from each application. For example, from the fastest times taken to build the primitive object, 60% were IDM' subjects whereas 40% were IM' subjects.

Table 13 - % of Subjects which Fell in the Fastest Half of Times to Execute each Task

Fastest Half Times	**IDM (%)**	**IM (%)**
Build primitive object	60	40
Build cut object	60	40
Build abstract object	50	50
Build revolution object	30	70
Build composite object	60	40
Build general object	40	60
All objects combined	55	45

These times however indicates that in IDM (physical) the subjects built the primitive, cut, abstract and composite objects quicker or as quick than in IM (geometrical) where subjects were quicker at building the revolution and general objects.

The table below shows the mean and standard deviation for times taken to execute each of the tasks.

Table 14 - Means and Standard Deviations for Times Taken to Execute Each Tasks

	IDM	**IM**
Build primitive object	235 ± 248	187 ± 156
Build cut object	376 ± 312	550 ± 443
Build abstract object	598 ± 352	495 ± 301
Build revolution object	204 ± 129	154 ± 122
Build composite object	668 ± 330	865 ± 379
Build general object	770 ± 459	630 ± 314
All objects combined	475 ± 139	480 ± 136

Table 14 shows that on average the cut and composite object will be built quicker in IDM (author's physical application) than in IM (author's geometrical application) whereas the primitive, abstract, revolution and general objects will be built quicker in IM rather than IDM. Furthermore when all objects are combined no real difference exists between the two methods. However the analysis of variance [44] shows that those differences in means are not significant at the 5% level, that is, they occurred by chance.

In addition, when it came to build the abstract object, 60% of IDM users did use the force, in IM 90% moved vertices. To build the general object, just half of IDM users did use the forces and 80% of IM users moved vertices.

For the mean and standard deviation of other variables please refer to Appendix VII on page 184.

6.7.2 Linear Regression Results

These are the significant correlations found (at the tabulated 5% level) when attempting to explain some dependent variables based on application:

- IM (geometrical application) produced the highest level of satisfaction with the abstract, revolution and composite objects provided that the effect of handedness was taken into account, that is, included in the regression model, in the abstract object; the effect of handedness and execution time were taken into account in the revolution object; and the effect of the execution time was taken into account in the general object. (Table 53, Table 54 and Table 55 on page 209).
- IM (geometrical application) produced the highest level of satisfaction with all the task combined when the effect of handedness was taken into account (Table 56).

Other significant correlations (at the tabulated 5% level), independently of application, were also found:

- Execution times for the tasks were associated in three instances with the level of satisfaction with the tasks. The less time a subject spent executing the cut, revolution or composite object the more satisfied s/he was with its final result provided: the effect of application and handedness were taken into account in the revolution object and the effect of application was taken into account in the composite object. (Table 57, Table 54 and Table 55 on page 209).
- Based on combined times for all tasks the longer a subject thought about the tasks the longer it took him/her to execute it when the effect of computer expertise was taken into account. On the other hand, a computer expert was faster at executing the tasks when the effect of thinking time was taken into account (Table 58 on page 210).

Furthermore, as in the first analysis, twenty two models were fitted but instead of presenting each individual one here, a general table is given. The twenty two tables however are described and interpreted accordingly in Appendix X on page 220 since these can be used in future work.

For more details and the data in statistical form please refer to Appendix IX on page 207.

The general table consists of the most predominant occurrence of each variable per application.

Table 15 - Resulting General Table

	IDM	IM
Age		+
Sex	Female	Male
Group (arts/sciences)	Arts	Sciences
Previous technical drawing experience		No
Computer experience	+	-
Spatial ability score		-
Number of visual answers in VAK quest.	-	+
Num. of kinaesthetic answers in VAK qst		-

Table 15 shows that the best user of IDM was female, doing an arts related course, with computer experience and a low number of visual answers in the VAK questionnaire.

On the other hand, IM's best user was an older male, doing a science related course with no previous technical drawing or computer experience, with a low spatial ability score and number of kinaesthetic answers in the VAK questionnaire but with a high number of visual answers in the VAK questionnaire.

6.8 Discussion of Results

The results obtained from the first analysis amongst the geometrical applications showed that the application built by the author was preferred and indeed performed better than the other two. In general terms this might have occurred because IM incorporated in its design the use of few and reasonably sized icons; consistency throughout the application, be it with the style of interaction, presentation or feedback; minimized screen clutter; simplified operations as much as possible and kept them to requirements. In addition, another requirement which arose from observation was to take care when placing the access to the tools. Mistakes can occur and if two completely different operations are not well distinguished, the user is bound, at least once, to produce an undesired effect. Similarly, operations which at a glance might appear similar, such as *delete* and *duplicate*, should be kept well apart.

The results not only showed that IM was preferred but also gave us a profile of a user which can benefit most from what each application had to offer. However some of these user characteristics differ from application to application and one should look at differences amongst applications in order to understand such differences in profile. For example, as shown a user with no previous technical drawing experience performed better in IM than in I3DM or Swivel3D. One possible explanation for this could be the fact that in I3DM menus with technical terms are used and in Swivel3D the use of cross, side and top sections to build objects would demand a more technical approach.

Likewise, a computer expert preferred IM or I3DM over Swivel3D possibly because IM and I3DM used a Silicon Graphics machine whereas Swivel3D used a Macintosh. Their different underlying styles or presentation of interface might account for the difference.

A user with a high number of visual answers in the VAK questionnaire also preferred IM or I3DM over Swivel3D. This could be due to the fact that IM and I3DM worked with 4 views of the world whereas Swivel3D worked with just one.

The second analysis comparing the physical and the geometrical methods showed that there was no significant difference in the use or not of the forces, even if one looks into the number of subjects that used the forces at all during the whole experiment or actually thought of using it when two particular tasks were given out. In total, 70% at one time during the experiments used the forces against 90% which moved vertices, showing no real improvement. 50% thought about using the forces when given the abstract object against 70% who thought about moving vertices. Only 30% thought about using the forces when given the general object against 70% who thought about moving vertices. These suggest that simulating forces does not help in general and therefore may not be worth the computational effort. Moreover it is important to notice that all of those who thought about using the forces or moving vertices did so.

Now the differences presented by the user's profile given by the linear regression analysis can be examined.

A user doing an arts related course will prefer IDM (with forces) whereas a user doing a science related course will prefer IM (without forces). Such findings might indicate that arts students prefer IDM because it is more related to reality and it does not demand much precision, whereas the geometrical method might seem more precise and be preferred by the sciences student. However, a computer expert will do better in IDM (with forces) than in IM (without forces) possibly because the steps needed to apply the forces are more demanding than the ones taken when just moving vertices, that is, a force needs to be defined in terms of intensity and direction before it can be applied whereas a vertex can be moved straight away. This also may reflect that this aspect of IDM's user interface is more complicated than IM's.

Now the findings from the linear regression analysis can be used in an attempt to investigate the relatively poor performance of the physical method.

Instead of a general table, presenting the major occurrences for each variable per application, a table was produced for each set of indicators, i.e. level of satisfaction, use of tools, time to think about each task and time to execute them. In addition the main characteristics of the subjects used in the experiments for each application in relation to each other were gathered. Using these two pieces of information the following observations could be made.

The user's characteristics in terms of level of satisfaction only with IDM (with forces) is an older male, with previous technical drawing experience, a high number of kinaesthetic answers in the VAK questionnaire and an arts student. However, the majority of students in IDM's sample were young females with no previous technical drawing experience, which could explain the low level of satisfaction with IDM in the raw data.

Likewise, if one looks into the characteristics of the users with respect to executing the tasks only one sees that IDM's user should be an older female, with previous technical drawing experience, a computer expert, with a high number of auditory and a low number of kinaesthetic answers in the VAK questionnaire, and a sciences student who didn't have problems with the mouse. And yet the majority of IDM users were young females, with no previous technical drawing experience, novices, with a low number of auditory and a high number of kinaesthetic answers in the VAK questionnaire and the majority also had problem with the mouse.

These could be some reasons why the observed level of satisfaction and the times taken to execute each tasks in IDM were low.

Other possible reasons come from the fact that the forces took longer to be calculated compared with just moving vertices, a 2D device might be appropriate to move vertices but might not be when applying forces, maybe a 3D input device would reduce the number of steps needed to use the forces and this could also be a reason people preferred to group a number of objects together instead of deforming an existing one.

6.9 Discussion of Methodology

Throughout this research steps were taken in order to reduce the influence of elements such as user interface in the analysis of the methods.

The first analysis had the purpose of testing the standard of the underlying user interface; where possible, tutorials were the same, instructions were written so that subjects always received the same information.

The results from the second analysis however can still be due to factors such as the difference in interaction when using a deformation method, the difference in sample used, the way in which the method is presented, the speed and smoothness of the interaction or the method itself. It is a very difficult task to separate these factors but maybe some more steps can be taken in an attempt to isolate their effect.

Table 12 on page 106 shows that for the revolution and the composite objects the subjects were more satisfied with IM, the geometrical application, than with IDM, the physical application, even though their user interface for these tasks were the same. These might be due to the difference in the samples. In the case of the revolution object Table 108 on page 226 shows a correlation with previous technical drawing experience whereas IDM's sample had a majority of subjects with no previous technical drawing experience. In the case of the composite object Table 109 on page 227 shows a correlation with males whereas IDM's sample had a majority of females.

Another factor however might have contributed or indeed caused these differences in terms of level of satisfaction. Although those particular tasks did not require the use of deformations the subject was presented with tutorials which explained a deformation method. This maybe should be avoided in the future by presenting to the subject first a tutorial which does not include the deformation method and then first ask him/her to execute the tasks which do not involve deformation. This assures that the subject receives exactly the same information for both methods. A second tutorial explaining the deformation method alone should then be given followed by the tasks related to deformation. Thus if any difference is found it cannot be attributed to the difference in tutorial.

Factors which might have influenced the differences found between the deformation methods are: the process of interaction, that is the number of necessary actions, the smoothness of the interaction or indeed the method itself. With the advance in technology, which will be discussed in the next chapter, 3D input devices might provide an answer to the number of necessary actions for interaction whereas, and more importantly, the increase in processing power makes interaction faster and smoother. These solutions however might create other influencing factors so it would be advisable to try to isolate their effects. A more in-depth study with the subject might be more appropriate, asking him/her more specific questions about the interaction and the method itself.

6.10 Summary

This chapter presented the raw data and linear regression analysis conducted in the data collected during the experiments. Two analyses were made, the first compared the application built in this work without the forces (IM), i.e. geometrical, against the other two geometrical applications I3DM and Swivel3D. The purpose of this analysis was to compare the author's geometrical application with the others at the user interface level. Comparing IM with other geometrical applications did show that IM's interface was of an acceptable standard and its effect in the analysis of the methods would be minimised. The analysis showed that subjects were more satisfied or as satisfied with IM than the other two applications, that they found IM tools easier to locate and to use and finally that overall they executed the tasks faster in IM than in the other two applications. Furthermore, the linear regression analysis identified the characteristics of users who would be more satisfied, find the tools easier to locate and use, and be quicker at executing each tasks, in each of the applications (Table 11 on page 105).

With these results in hand the second analysis was made, ruling out the possibility that any differences found would be the result of the overall interface used. So the second analysis consisted of the two applications built by the author, one to represent the physical method (IDM), with the forces, and the other to represent the geometrical (IM), without the forces. The raw data for this second analysis showed that the method which subjects were more satisfied with and the one in which they performed the tasks quicker was in fact the geometrical one (IM). The raw data also showed that, when subjects were given the choice to use the forces or not, 50% did. Thus, when viewed alone, having or not having the forces did not make any significant difference, and when viewed in comparison with the geometrical method the latter is preferred overall.

As with the first analysis, the linear regression was also applied and again users' characteristics were found for each of the applications (Table 15 on page 109).

These results were then followed by a discussion which attempted to explain why an Arts student might execute the tasks quicker on a certain application but slower at another, and also to investigate why there was no apparent difference, and even a decline, when forces were introduced.

The first part of the discussion, which referred to the characteristics found for each application, was based on the differences amongst applications and the possible reasons why one might be preferred over another.

The second part, which investigated the relatively poor performance of the forces, was based on the differences between applications but also on the characteristics of the sample used.

Now that the results have been presented and discussed, the next chapter will present a summary of this thesis highlighting its main points, a list of contributions and suggest future work.

Chapter 7 Conclusion

7.1 Thesis Summary

The aim of this work was to investigate the use of physical deformations against the use of geometrical deformations in the creation and manipulation of 3D objects. Thus, in order to carry out such investigation two version of an application were built, one applying the physical method (with forces) and the other applying the geometrical method (without forces, i.e. just moving vertices). The method chosen to simulate the physical deformations was the Finite Element Method (FEM) which was presented in detail in Chapter 3. In a first analysis the geometrical application was compared against existing commercial applications. The applications used, including the developed ones, had their object and operations and interface presented in Chapter 4. The method used for comparison, the design of questionnaires, the pilot studies, the description of the experiments themselves and how they were conducted were presented in Chapter 5. The results of such analysis, discussed in Chapter 6, showed that the developed application was preferred and had a better performance than the other two commercial ones. This could have been due to the design characteristics of IM: use of few and reasonably sized icons, consistency, minimized screen clutter and, simplified operations restricting them to requirements. As a result of observations, the author also added that two completely different operations should be well distinguished and not be put too near each other. In addition to these results, a set of characteristics was found which defined the best user for each application. These were in the case of IM (built geometrical application) a male, doing an arts related subject, with no previous technical drawing experience but with computer and previous CAD experience, who has a low score in the spatial ability test but a high number of visual and auditory answers in the VAK questionnaire, and finally, spends more time doing the tutorial. In the case of I3DM, a younger female, with previous technical drawing experience and computer experience but no previous CAD experience, who has a high number of visual but a low number of auditory answers in the VAK questionnaire, and finally, spends less time doing the tutorial. And for Swivel3D, an older female doing an arts related subject, with previous technical drawing and CAD experience but with less computer experience, and, with a low number of visual and auditory answers in the VAK questionnaire.

Based on these facts the analysis of the methods could take place and its results showed that there were no significant differences between the use or not of forces, indicating that for the tasks performed simulating forces may not be worth the computational effort. Again a set of general characteristics was found, which, as presented in the previous chapter were in the case of IDM a female, doing an arts related course, with computer experience and a low number of visual answers in the VAK questionnaire. On the other hand, IM's best user is a older male, doing a science related course with no previous technical drawing or computer experience, with a low spatial ability score and number of kinaesthetic answers in the VAK questionnaire but with a high number of visual answers.

Such characteristics were also used in groups in an attempt to explain the relatively poor performance in the use of forces. It was found that the sample used in IDM contradicted the characteristics for a good performance, and this could be the cause of IDM's indifferent performance when compared with IM.

7.2 Summary of Contributions

The main goal of this work has been an investigation into the use of physical and geometrical deformations in the interactive creation of 3D objects. This goal has been achieved and it forms the main contribution of this thesis but other contributions were also made while in pursue of that goal. These are as follows:

- *The presentation of a survey of existing physical and geometrical methods of deformation;*

  The most common techniques were described making it a source of reference for future work.
- *The implementation of a user interface to support a physical and a geometrical method of deformation;*
- *A graphics tutorial for computer novices which can be adapted according to the application used;*

  The tutorial has been developed as a number of steps to be followed by a user with clear instructions for the user interface and important definitions. This tutorial can be also be adapted, as done in this work, to suit any application. The logical sequence used to design each step was tested and showed to be successful.

- *The definition of a methodology for a user based study of deformation methods and user interface which uses clay models, spatial ability test, introduction sheet, graphical tutorial, questionnaires and observation sheet;*

  This methodology proved to be successful in the analysis of tasks involving 3D views or awareness. Clay models improved significantly the recognition of objects. Spatial ability tests, although not in this case, could have a correlation with the response variable of interest. The use of an introduction sheet made subjects more at ease with the whole experiment because they knew what to expect. The graphical tutorial proved necessary for dealing with novices but needed to be explicit enough as not to give a wrong impression about the difficulty of the learning process. Questionnaires provided background and self-evaluation information and important feedback about the whole procedure. And finally, observation sheet collected information from the point of view of the researcher. All these elements together formed a solid platform on which the analysis was based.

  However, improvements can always be made and some suggestions as to improve this methodology were given in Section 6.9 on page 112. These included the use of two separate tutorials given at different times during the experiment, one explaining the underlying user interface and another explaining the deformation method. The use of a more in-depth analysis with the user in order to gather more specific information about the deformation method and interaction.

- *The identification of a number of subject characteristics for a group of graphical applications when compared against each other;*

  These characteristics will be useful in any work involving either deformation method. They can be used as a criteria for decision making (for example, in design), selecting a more specific sample of a population to suit a particular task hence minimizing the number of external variables, or to help in the understanding of a particular behaviour of a random sample.

- *The investigation into the use of a physical against a geometrical method of deformation for the execution of a specified number of tasks involving the interactive creation of 3D solid objects.*

  The investigation as a whole produced statistical data which can be used for comparisons with future work in the area. The finding that the use of physical simulated forces did not seem to improve the satisfaction and times taken to execute the tasks given suggests that, although a lot of research has gone into "replicating" reality, this effort, in the case of the interactive creation of 3D solid objects, might be of limited value. It seems that people see a computer as a tool to "improve" reality and to have control over situations. In the creation of 3D solid objects it seems that the predictable but not precise outcome of a physical deformation gives way to the more controllable and precise outcome of a geometrical only deformation.

Although these findings are significant, some caution is necessary here. A commonly held belief states that processing power doubles every year. Since this research began processing power has increased by a factor of between sixteen to thirty-two. Clearly, if this research was being started now, a much more complex and realistic physical model could have been implemented embodying a model which would also stand some chance of success on standard workstations. For example, the model might include a complete simulation of elasticity [60], plasticity and fracture [62], and where more than one object is concerned, collision detection and response [34]. A very important consequence of the advance in technology is that the interaction with the model itself would be faster and smoother, which might bring a more realistic feeling to the user and make the physical and geometrical models more comparable in terms of speed. Obviously the findings of this research cannot be generalised to more complex or more realistic physical models. However, future research could use the results of this work as a starting point for hypothesis formation.

As processing power advances so does technology. This research was based on a 2D input device and a normal 2D display and no extra accessories, such as stereoglasses, were used. This choice of hardware was made based on the fact that existing geometrical applications were needed for the analysis of the user interface. Applications which used the most common technology at the time. Now 3D input devices and 3D displays are becoming more widely available. Virtual reality, in particular, is an area which sees the proliferation of this technology. Again, if this research was to start today, it would make sense to use such 3D devices since the focus of attention is on 3D solid objects. Clearly the introduction of more sophisticated input devices would require a more complex experimental design with more factors to control.

7.3 Future Work

Other investigations similar to this work into the use of physical against geometrical method of deformation could be carried out in order to test the results presented in the previous chapter.

The manipulation of 3D objects through an input (mouse) and output (display) 2D device has it constraints. Therefore this investigation could be extended by the use of an input device with more degrees of freedom, such as a joystick, bat [69], desktop bat [53,57], data glove, polhemus or trackball, and the addition of immersive virtual reality or stereoscopic images, which might be more appropriate for the handling of deformation.

The interface itself could make use of 3D-widget design [20,30,37,56] to support more degrees of freedom.

An investigation could be carried out to evaluate the extent to which tactile feedback might affect the results.

It would be interesting to know if a similar investigation to the one presented in this work done with a complete physical model would result in the same findings in relation to the geometrical model.

And finally, if the changes in methodology identified by the author were made would these changes produce the desired results?

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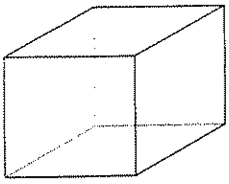
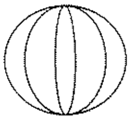
Appendix I Object Card Drawings

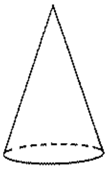
1 - cube



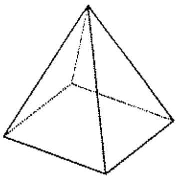
2 - sphere



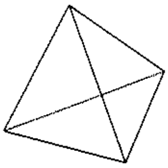
3 - cone



4 - pyramid

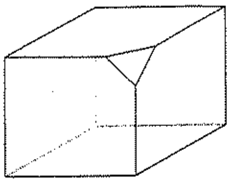


5 - tetrahedron

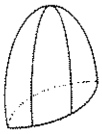


6 - cylinder

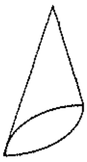
1 - cube without a corner



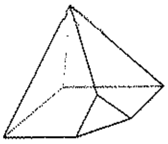
2 - oblong with diagonal cut



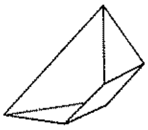
3 - cone with diagonal base



4 - pyramid without a corner on base



5 - tetrahedron without 2 adjacents corners



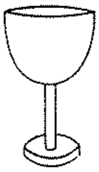
6 - cylinder with diagonal base

1 - lampshade

2 - vase

3 - fruit-bowl

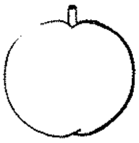
4 - wine glass



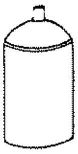
5 - bottle

6 - umbrella

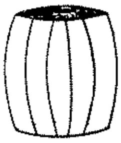
7 - apple



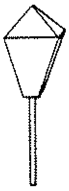
8 - spray-can



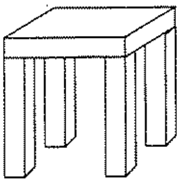
9 - barrel



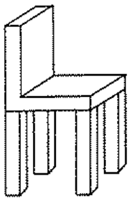
10 - lamp-post



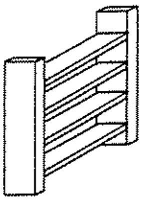
1. table



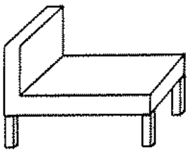
2 - chair



3 - bookshelf with 4 shelves

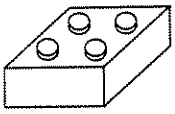


4 - bed with headrest

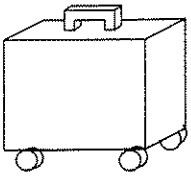


5 - traffic-light

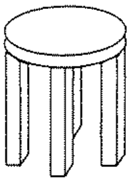
6 - lego brick



7 - luggage with 4 wheels



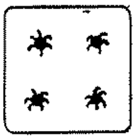
8 - round chair without back



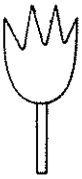
1 - aeroplane

2 - pineapple

3 - cushion with 4 buttons



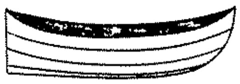
4 - tulip



5 - fish

6 - dinosaurus back

7 - ship hull



8 - bird

Appendix II Experimental Protocol

1. Have machine available and application ready to start. On a table: drinks (water) and cups, clay models grouped by task, elements of experiment (introduction sheet, tutorial, etc.) in order and ready, 'quiet please, experiment in progress' signs around the area.
2. Welcome subject and verbally thank him/her for coming, point to drinks and cups and tell him/her to help himself/herself. Point to designated seat, verbally introduce subject to the machine he/she will use. Hand out the introduction sheet.
3. Note down the starting time for the experiment.
4. Collect the introduction sheet and ask subject if he/she understood it. Hand out a pen and Questionnaire 1. Ask him/her to fill it in and return it to you when finished.
5. Collect Questionnaire 1. Hand out respective tutorial and verbally explain to subject that he/she must read the tutorial and follow all the steps indicated by numbers and underlined instructions, that there is no time limit to complete it and that you will sit next to him/her in order to assist him/her if necessary. Start timing tutorial.
6. Sit slightly back from the subject so not to interfere with his/her attention. Pay attention to see if subject is following the instructions, if not, gently interrupt and point out that he/she missed a step. If the subject is having problems with any task or makes gestures which indicate he/she didn't understand, offer some help to explain it.
7. Once the tutorial is completed ask subject if he/she understood all the steps and if he/she has any questions. Leave tutorial with the subject and tell him/her that he/she can refer back to it if he/she wants. Tell subject also that this is not a memory test and that you don't expect him/her to memorize the sequence for all the operations, and that you will help him/her if needed. Stop timing tutorial.
8. Hand out Questionnaire 2. Verbally explain that you will give him/her an object at a time to build starting by giving him/her a set of cards face down, he/she will pick one up and be asked to give it back to you without looking at it; you will go to the table and pick the corresponding clay model, you will then give the clay model to him/her. Still verbally, explain that the clay model is to be used as a guide only, that you are interested in the overall shape and that he/she doesn't need to produce an exact copy. Pick up Questionnaire 2, show subject question 1 and explain that before he/she starts to build the object using the computer he/she should describe in no more than 4 steps how he/she intends to build the object. The description is to be according to how he/

she thinks of doing it, independently of application. And that he/she should write it with his/her own words, not describing the steps for the operations like 'press such and such icon'. Explain also that he/she is not bound by these steps, that is, he/she can change his/her mind if wanted. Once he/she finish describing it, he/she will have a maximum of 20 minutes to build the object. When he/she feels happy with it, he/she should tell you that he/she finished. Show questions 2 to 5 in the questionnaire and explain that he/she will answer them after the object is finished. This will be repeated 6 times, one for each object.

9. Pick up first set of cards. Ask subject to pick one up and give it back to you. Pick the corresponding clay model. Give it to him/her and verbally state what it is. Ask subject to answer question 1. Sit slightly back from the subject and start timing thinking time. When subject indicates that he/she finished stop timing thinking time. Start timing execution time. Watch subject, note down tools used, that is, cut, forces, move vertices, etc. When subject indicates he/she finished stop timing execution time. Ask subject to answer questions 2 to 5.
10. Repeat previous step for all tasks. Between tasks 3 and 4 have a little pause and ask subject if he/she would like something to drink.
11. Once all tasks are completed position the corresponding clay models in order of execution with their corresponding task number facing forward. Show subject question 31 and ask him/her to number the tasks in order of difficulty.
12. Collect Questionnaire 2. Hand out Questionnaire 3 and ask the subject to answer it.
13. Collect Questionnaire 3. Ask the subject if he/she has any comments. Talk to him/her as a debrief session. Thank him/her for taking part. Walk him/her to the door. Note down end time of experiment.

Appendix III Experiment Introduction Sheet

How the experiment will be conducted ...

Thank you for taking the time to do this experiment, it will be of great help to my research.

The objectives of this experiment are to present you with a graphical package, ask you to use this graphical package to build six 3D objects and answer some questionnaires.

Some data will also be collected by observing you during execution of your tasks.

If at any time you do not understand something or want some sort of clarification over any matter, please do not hesitate to ask the researcher.

The experiment itself will be as follows:

1. You will be asked to fill in a questionnaire about yourself.
   Tell the researcher when finished.
2. You will read a fact-sheet about the package.
3. You will go through a tutorial in order to explore what you can and can not do in the package.
   Particular attention will be spent on:
   - how to create an object
   - how to create surfaces of revolution
   - how to duplicate objects
   - how to group/connect two objects

   Tell the researcher when finished.
4. You will be asked to produce an object (maximum time 20 minutes). You will be given a clay model to be used as a GUIDE ONLY; however, the object must have the minimum structure specified in the model, i.e. a chair with 4 not 3 legs.
   You will be asked to describe in up to 4 short statement how you intend to do the object.
   You will use the computer to produce the object.
   Tell the researcher when finished.
   You will be asked to answer some questions about the object you created.
5. Step 4 repeated 6 times.
6. You will be asked to fill in a questionnaire about the package you used. These questions will require multiple choice and written answers.

Your questionnaires and the times taken to complete each object (step 3) will be collected into a database and its analysis will be used in the researcher's thesis.

Note: All the information collected will be in confidence.

Appendix IV Experiment Tutorials

IDM

(Interactive Deformable Modeller)

Tutorial

Please follow the tutorial the best you can, it is important you understand all the actions explained in it, you will need them later on.

Note: Throughout this tutorial the term **vertex** means an intersection point between two or more lines in a mesh that represents an object or any corner point that forms an object.

How to create an object in IDM:

There are 2 ways in which to create an object in IDM:

- by extrusion or
- by revolution.

1. Creating an object by extrusion

Extrusion means that an outlined 2D shape is extruded (i.e. pushed back) a certain distance to form a 3D solid. The **default distance** for extrusion is 120 units which can be changed.

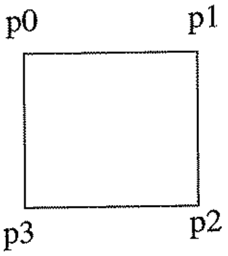
Activity 1 - Turn grid on

Choose the ***Options*** menu then ***Grid On/Off***.

Note: Each square in the grid represents 100 units.

Activity 2 - Create a cube by extrusion

Select the drawing icon ✎ (top left green area) which will become black (already selected when the package is being used for the first time). Use the left mouse button to draw the following 2D outline in any of the top, front or left views. To **draw** the outline click and release the left mouse button where you want your outline to start (p0). You will see that a line now will follow the cursor from the first point. Click and release the mouse again where you want the second point to be and so on until your outline is complete. To **finish** the outline just close it by clicking back on the first point (p0). The 3D object will then be formed by extruding this outline. Note, the point numbers don't appear:



Activity 3 - Move the object

Select the object move **icon** ✥ (top left yellow area) then click and hold the **left** mouse button on the object you want to move. **Drag** the mouse up/down/left or right and the object will move accordingly. To finish just **release** the mouse button. To move the object in or out just click and hold the **middle** mouse button and drag the mouse up(in) or down(out). Note, the **red color** indicates which is the **current object**. Note: this operation doesn't work in the ***Perspective View***.

Activity 4 - Rotate the object

Select the object rotate **icon** ⟲ (top right yellow area) then click and hold the **left** mouse button on the object you want to rotate. **Drag** the mouse up/down/right or left and the object will rotate accordingly. To finish just **release** the mouse button. To rotate the object around the z axis just click and hold the **middle** mouse button and drag the mouse left or right. Note, the **red color** indicates which is the

current object. Note: this operation doesn't work in the *Perspective View.*

Activity 5 - Select shade object

Click on the shade icon ■ .

Activity 6 - Scale the object

Select the object scale **icon** (bottom left yellow area) then click and hold the left mouse button on the object you want to scale. **Drag** the mouse up if you want to make the object bigger or down to make it smaller. To finish just **release** the mouse button. Note, the red color indicates which is the current object. Note: this operation doesn't work in the *Perspective View.*

Activity 7 - Move the camera

Select the camera move **icon** (right blue area) then click and hold the **left** mouse button in any of the views (top, front, side or perspective). **Drag** the mouse to indicate the direction. To **finish** just release the mouse button. To **zoom in** or **out** just click and hold the **middle** mouse button and drag it up(in) or down(out).

Activity 8 - Rotate the camera

Select the camera rotate **icon** (left blue area) then click and hold the **left** mouse button in any view (top, front, right or perspective). **Drag** the mouse to indicate the direction. To finish just release the mouse button. To rotate the camera around the z axis just click and hold the **middle** mouse button and drag it left or right.

Activity 9 - Select wire frame object

Click on the wire frame icon □ .

Activity 10 -Delete the object

To delete an object in IDM first **select** "Delete Object" under the "Options" menu then **click** on the **object** you want to delete. Note: this operations doesn't work in the *Perspective View.*

Activity 11 -Create a long rectangle

Now change the default distance for extrusion by choosing the "Parameters" option under the "Options" menu to a bigger number and repeat activity 1.

Activity 12 -Make the wire mesh finer

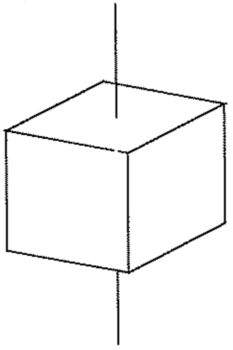
Now click the mesh icon ▨ three times with a pause each time to see the mesh that forms the object get finer. Note: Usually the first click produces just internal refinement.

Activity 13 -Delete the object

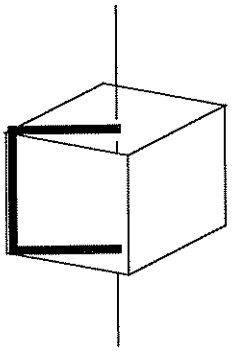
2. *Creating an object by revolution*

Revolution means that an outlined 2D shape is revolved (i.e. turned round) to form a 3D solid. This revolution occurs around an imaginary axis which in IDM's case is formed by the first and last points of an outline. The default **number of segments** formed by the rotation is 12 (i.e. the object is formed by 12 "slices").

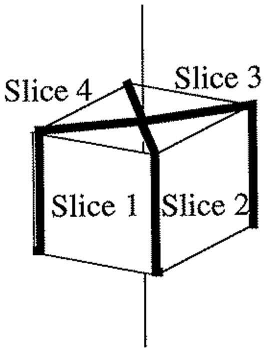
For example, if you want to create a cube the imaginary axis would be:



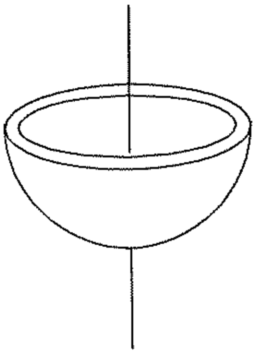
the outline would be:



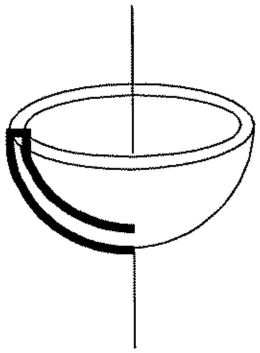
and the number of segments (slices) would be 4:



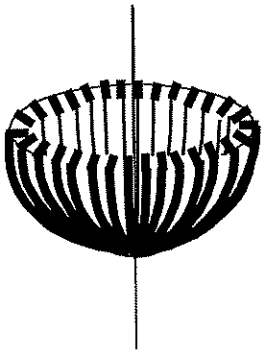
If you wanted to create a fruit bowl the imaginary axis would be:



the outline would be:

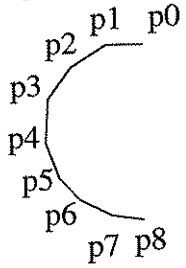


and the higher the number of segments (slices) the smoother the bowl would be:



Activity 14 -Create a sphere by revolution

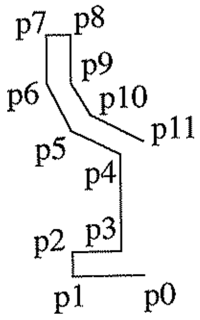
Select the drawing icon ✎ (top left in green area), use the left mouse button to create the following outline but instead of clicking back on the first point (p0) of the outline to **finish** double click on the **last point** (p8), leaving the outline with an opening between the last and first points. This opening will serve as the imaginary axis for the revolution of the outline. Note, the point numbers don't appear:



Activity 15 -Delete the object

Activity 16 -Create a wine glass (hollow object) through revolution

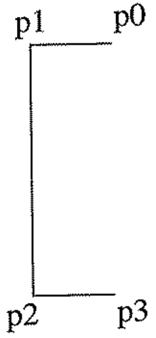
Follow the instructions given for activity 13 with the following outline. Note: the numbers don't appear.



Activity 17 -Delete the object

Activity 18 -Create a long rectangle

Now change the default **number of segments** by choosing the ***Options*** menu then ***Parameters***. Another screen will appear containing 3 scales. Change the one on the right (***Number of Segments***) to 4. To change the parameters' bar one unit at the time, click in the sliding **bar** above or below the sliding **button** as necessary. Now click ***OK*** then use the left mouse button to create the following outline, double-clicking in the last point (p3). Note, the point numbers don't appear. You will end up with a **long rectangle**.



Activity 19 -Duplicate the object

Select "Duplicate Object" under the "Options" menu then **click** on the object you want **duplicated**. The new object will appear in red (current object) next to the original one. Note: this operation doesn't work in the ***Perspective View***.

Activity 20 -Connect two objects

First make sure you have the object displayed as a wire frame structure so you can see where all the vertices are.

Now **select** the "hammer" **icon** (green area) then use the left mouse button to click on the **vertex for connection** on the **first object**. Then again using the left mouse button click on the **vertex for connection** on the **second object**. The first object will move to where the second one is until the 2 points are connected. Now **rotate** the **connected** object by selecting the object rotate icon , clicking and holding on the object and moving the mouse to rotate it.

This operation is very useful for aligning objects after a connection. A connected object can be **rotated or scaled** provided it has just one connection point, **otherwise all** objects connected will rotate or scale. Note: this operation doesn't work in the ***Perspective View***.

Activity 21 -Disconnect the objects

Select the "broom" **icon** (top right green area) then **click** on the object you want to disconnect. Note: this operation doesn't work in the ***Perspective View***.

Activity 22 -Delete one of the objects

Activity 23 -Split the object into two

First **press** the "knife" **icon** (green area). A **yellow cutting plane** will appear. **Move** the **object** or the **cutting plane** accordingly and press the "knife" icon again. The cutting plane will **cut** the current object (red) if the object intersect the plane. Now you have two objects instead of one. Note 1 : this operation doesn't work in the *Perspective View*.

Note 2 : the **cutting plane is an object** like any other so you can move, rotate and delete it in the same way you can manipulate other objects.

Activity 24 -Delete one of the objects

Activity 25 -Delete the cutting plane

Activity 26 -Reshape the object

IDM uses forces to reshape objects. **Forces** are applied to vertices reshaping the object by simulating physical reactions. First, to apply the forces at least **2 fix vertices** need to be specified. To specify the fix vertices first **select** the "hammer" **icon** (green area) then click on the vertices you want it to be fixed, a **blue square** will appear on each fix vertex. Next you need to specify which **vertex/vertices** will receive the **force(s)** and which **direction** and **strength** the force(s) is going to be. First **select** the "force" **icon** , click on a vertex that will receive the force (a **green square** will appear on the vertex) then **move** the mouse accordingly (a line will follow it) to define the **direction** of the force (direction of the line) and its **strength** (length of the line). To **define** it just click the mouse button again. Repeat the process to define as many forces as you want. Now that the forces and fix points are defined the simulation can start. To do so just **click** the "apply" **icon** to **start** the simulation (you will see the forces deforming the object) and **click** the "apply" icon again to **stop** it. Note: this operation doesn't work in the *Perspective View*.

Activity 27 -Clear all forces and fix points

Select the "broom" **icon** (top right green area) then **click** on the object you want to clear and you will see that all the **green and red** squares will **disappear**. Note: this operation doesn't work in the *Perspective View*.

Note: To clear just one point at the time, first select the appropriate icon (hammer or force) then click on the point you want to clear.

Drawing

Fix and connect points

Define force points

Apply forces

Move object up/down/left/right/in/out

Scale object

Move camera up/down/left/right/in/out

□ Wire frame object

Clear all fix, connection and force points

Split an object into two

⊠ Makes the current object's mesh finer

Rotate object around x, y and z axes

Rotate camera around x, y and z axes

■ Shade object

IM

(Interactive Modeller)

Tutorial

Please follow the tutorial the best you can, it is important you understand all the actions explained in it, you will need them later on.

Note: Throughout this tutorial the term **vertex** means an intersection point between two or more lines in a mesh that represents an object or any corner point that forms an object.

How to create an object in IM:

There are 2 ways in which to create an object in IM:

- by extrusion or
- by revolution.

1. Creating an object by extrusion

Extrusion means that an outlined 2D shape is extruded (i.e. pushed back) a certain distance to form a 3D solid. The **default distance** for extrusion is 120 units which can be changed.

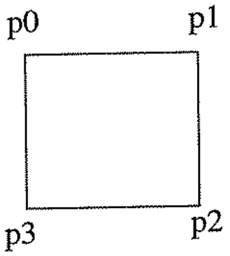
Activity 1 - Turn grid on

Choose the ***Options*** menu then ***Grid On/Off***.

Note: Each square in the grid represents 100 units.

Activity 2 - Create a cube by extrusion

Select the drawing icon (top left green area) which will become black (already selected when the package is being used for the first time). Use the left mouse button to draw the following 2D outline in any of the top, front or left views. To **draw** the outline click and release the left mouse button where you want your outline to start (p0). You will see that a line now will follow the cursor from the first point. Click and release the mouse again where you want the second point to be and so on until your outline is complete. To **finish** the outline just close it by clicking back on the first point (p0). The 3D object will then be formed by extruding this outline. Note, the point numbers don't appear:



Activity 3 - Move the object

Select the object move **icon** (top left yellow area) then click and hold the **left** mouse button on the object you want to move. **Drag** the mouse up/down/left or right and the object will move accordingly. To finish just **release** the mouse button. To move the object in or out just click and hold the **middle** mouse button and drag the mouse up(in) or down(out). Note, the **red color** indicates which is the **current object**. Note: this operation doesn't work in the ***Perspective View***.

Activity 4 - Rotate the object

Select the object rotate **icon** (top right yellow area) then click and hold the **left** mouse button on the object you want to rotate. **Drag** the mouse up/down/right or left and the object will rotate accordingly. To finish just **release** the mouse button. To rotate the object around the z axis just click and hold the **middle** mouse button and drag the mouse left or right. Note, the **red color** indicates which is the

current object. Note: this operation doesn't work in the ***Perspective View***.

Activity 5 - Select shade object

Click on the shade icon ■ .

Activity 6 - Scale the object

Select the object scale **icon** (bottom left yellow area) then click and hold the left mouse button on the object you want to scale. **Drag** the mouse up if you want to make the object bigger or down to make it smaller. To finish just **release** the mouse button. Note, the **red color** indicates which is the **current object**. Note: this operation doesn't work in the ***Perspective View***.

Activity 7 - Move the camera

Select the camera move **icon** (right blue area) then click and hold the **left** mouse button in any of the views (top, front, side or perspective). **Drag** the mouse to indicate the direction. To **finish** just release the mouse button. To **zoom in** or **out** just click and hold the **middle** mouse button and drag it up(in) or down(out).

Activity 8 - Rotate the camera

Select the camera rotate **icon** (left blue area) then click and hold the **left** mouse button in any view (top, front, right or perspective). **Drag** the mouse to indicate the direction. To finish just release the mouse button. To rotate the camera around the z axis just click and hold the **middle** mouse button and drag it left or right.

Activity 9 - Select wire frame object

Click on the wire frame icon □ .

Activity 10 -Delete the object

To delete an object in IM first **select** "Delete Object" under the "Options" menu then **click** on the **object** you want to delete. Note: this operations doesn't work in the ***Perspective View***.

Activity 11 -Create a long rectangle

Now change the default distance for extrusion by choosing the "Parameters" option under the "Options" menu to a bigger number and repeat activity 1.

Activity 12 -Make the wire mesh finer

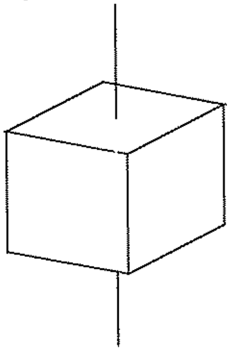
Now click the mesh icon ▩ three times with a pause each time to see the mesh that forms the object get finer. Note: Usually the first click produces just internal refinement.

Activity 13 -Delete the object

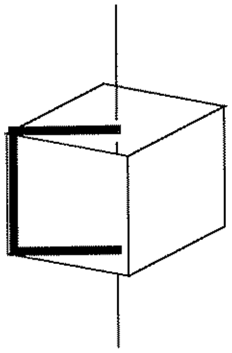
2. *Creating an object by revolution*

Revolution means that an outlined 2D shape is revolved (i.e. turned round) to form a 3D solid. This revolution occurs around an imaginary axis which in IM's case is formed by the first and last points of an outline. The default **number of segments** formed by the rotation is 12 (i.e. the object is formed by 12 "slices").

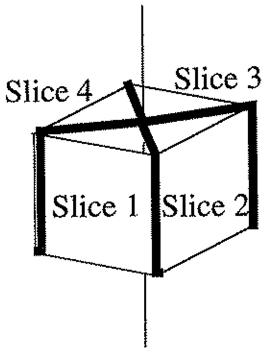
For example, if you want to create a cube the imaginary axis would be:



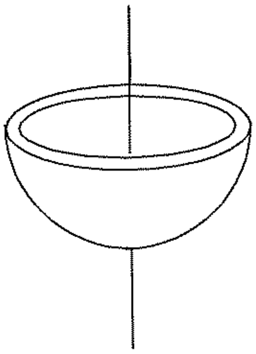
the outline would be:



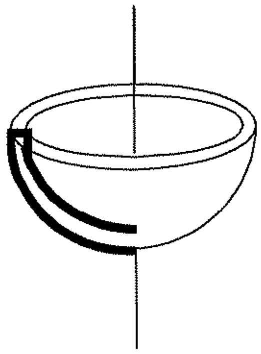
and the number of segments (slices) would be 4:



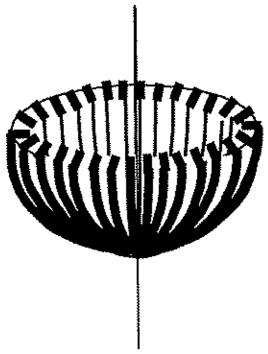
If you wanted to create a fruit bowl the imaginary axis would be:



the outline would be:

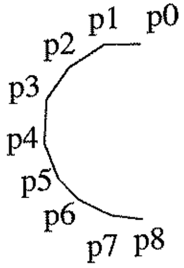


and the higher the number of segments (slices) the smoother the bowl would be:



Activity 14 -Create a sphere by revolution

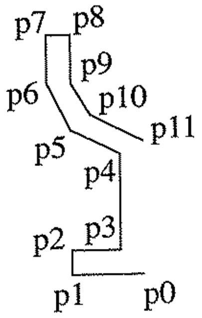
Select the drawing icon ✎ (top left in green area), use the left mouse button to create the following outline but instead of clicking back on the first point (p0) of the outline to **finish** double click on the **last point** (p8), leaving the outline with an opening between the last and first points. This opening will serve as the imaginary axis for the revolution of the outline. Note, the point numbers don't appear:



Activity 15 -Delete the object

Activity 16 -Create a wine glass (hollow object) through revolution

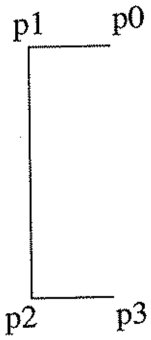
Follow the instructions given for activity 13 with the following outline. Note: the numbers don't appear.



Activity 17 -Delete the object

Activity 18 -Create a long rectangle

Now change the default **number of segments** by choosing the *Options* menu then *Parameters*. Another screen will appear containing 3 scales. Change the one on the right (*Number of Segments*) to 4. To change the parameters' bar more one unit at the time, click in the sliding **bar** above or below the sliding **button** as necessary. Now click *OK* then use the left mouse button to create the following outline, double-clicking in the last point (p3). Note, the point numbers don't appear. You will end up with a **long rectangle**.



Activity 19 -Duplicate the object

Select "Duplicate Object" under the "Options" menu then **click** on the object you want **duplicated**. The new object will appear in red (current object) next to the original one. Note: this operation doesn't work in the *Perspective View*.

Activity 20 -Connect two objects

First make sure you have the object displayed as a wire frame structure so you can see where all the vertices are.

Now **select** the "hammer" **icon** (green area) then use the left mouse button to click on the **vertex for connection** on the **first object.** Then again using the left mouse button click on the **vertex for connection** on the **second object**. The first object will move to where the second one is until the 2 points are connected. Now **rotate** the **connected** object by selecting the object rotate icon , clicking and holding on the object and moving the mouse to rotate it.

This operation is very useful for aligning objects after a connection. A connected object can be **rotated or scaled** provided it has just one connection point, **otherwise all** objects connected will rotate or scale. Note: this operation doesn't work in the *Perspective View*.

Activity 21 -Disconnect the objects

Select the "broom" **icon** (top right green area) then **click** on the object you want to disconnect. Note: this operation doesn't work in the *Perspective View*.

Activity 22 -Delete one of the objects

Activity 23 -Split the object into two

First **press** the “knife” **icon** (green area). A **yellow cutting plane** will appear. **Move** the **object** or the **cutting plane** accordingly and press the “knife” icon again. The cutting plane will **cut** the current object (red) if the object intersect the plane. Now you have two objects instead of one. Note 1: this operation doesn’t work in the *Perspective View.*

Note 2 : the **cutting plane is an object** like any other so you can move, rotate and delete it in the same way you can manipulate other objects.

Activity 24 -Delete one of the objects

Activity 25 -Delete the cutting plane

Activity 26 -Reshape the object

To reshape an object first make sure that there is **no icon selected** (black) in the green or yellow area, if there is, de-select it by clicking on it. Then just select the **vertex** you want to move by **clicking** on it, release the button and move the mouse to where you want it to be. To **finish** just press the mouse button to define where the vertex should be. You also can drag **more than one** vertex by clicking outside the object, holding and dragging the mouse to form a square selection over the points you want to move. Then **move** the mouse and the points will move accordingly. To finish just press the mouse button again.

Drawing

Clear all connection points

Connect points

Split an object into two

Makes the current object's mesh finer

Move object up/down/left/right/in/out

Rotate object around x, y and z axes

Scale object

Move camera up/down/left/right/in/out

Rotate camera around x, y and z axes

□ Wire frame object

■ Shade object

I3DM

(Interactive 3D Modeler)

Tutorial

Please follow the tutorial the best you can, it is important you understand all the actions explained in it, you will need them later on.

Note: Throughout this tutorial the term **vertex** means an intersection point between two or more lines in a mesh that represents an object or any corner point that forms an object.

How to create an object in I3DM:

To create a line, cylinder, cone, sphere, circle or curve just select any of them from the ***Create*** button. For lines and curves just click in the black drawing areas where you want the points to be and click ***Done*** to finish. For all the other objects you can change their parameters (such as height, radius, etc.) by typing them in the command line (bottom most window) and/or press return and the new object will be placed in the center of the screen.

Note: Each square in the grid represents 10 units.

To create other shaped objects you can use 2 other ways:

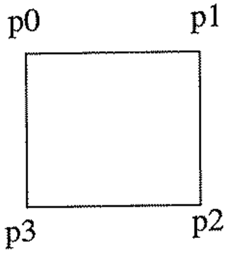
- extrusion or
- revolution.

1. Creating an object by extrusion

Extrusion means that an outlined 2D shape is extruded (i.e. pushed back) a certain distance to form a 3D solid. To **create** an extruded object in I3DM,Create a cube

Activity 1 - Create a cube by extrusion

Select ***Create*** then ***Lines***. Now use the left mouse button to draw the following 2D outline in the **front view**. To **draw** the outline click and release the left mouse button where you want your outline to start (p0). You can either release the mouse button or hold it down and you will see that a line now will follow the cursor from the first point. Click and/or release the mouse again where you want the second point to be and so on until your outline is complete. To **finish** the outline just close it by clicking back on the first point (p0). Note, the point numbers don't appear:



Now in order to make this outline a **face** (instead of just lines) select ***Surface*** then ***Face***.

Now select ***Create*** then ***Line*** again and draw the following line in the rigth view. Note, the point numbers don't appear:

This line appears in yellow (current object) and represents the direction and how much you want to extrude the object.

Go to ***Pick*** and choose ***Objects***. CLick in the outline which will also appear in yellow. Now go to the ***Surface*** menu and choose ***Extrude*** then ***Extrude Along***. The 3D object will then be formed by extruding the second object selected (the outline) along the first selected object (the line).

Activity 2 - Move the object

Select ***Pick*** then ***Nothing*** to clear all objects from being selected, then select ***Pick*** again with the ***Objects*** option. Now click on the object or objects you want to move. Then select ***Xform*** then ***Move***. **Click and drag** the mouse up/down/left or right and the object(s) will move accordingly. To finish just **release** the mouse button. Note, the **yellow color** indicates which is/are the **current object**(s) so if you want to move the current object you don't need to select ***Pick*** then ***Objects***, you just go directly to select ***Xform*** then ***Move***.

Activity 3 - Rotate the object

To rotate an object, first select ***Pick*** then ***Nothing*** to clear all objects from being selected, then select ***Pick*** again with the ***Objects*** option. Now click on the object or objects you want to rotate. Then select ***Xform*** then ***Rotate***. **Click and drag** the mouse up/down/left or right and the object(s) will rotate accordingly. To finish just **release** the mouse button. Note, the **yellow color** indicates which is/are the **current object**(s) so if you want to rotate the current object you don't need to select ***Pick*** then ***Objects***, you just go directly to select ***Xform*** then ***Rotate***.

Activity 4 - Shade a view of the object

In the view you want the object to be shaded click and hold the **right mouse button** and choose ***Shaded***.

Activity 5 - Scale the object

To scale an object, first select ***Pick*** then ***Nothing*** to clear all objects from being selected, then select ***Pick*** again with the ***Objects*** option. Now click on the object or objects you want to scale. Then select ***Xform*** then ***Scale Uniform or Scale Non-Uniform*** as desired. **Click and drag** the mouse up/down/left or right and the object(s) will scale accordingly. To finish just **release** the mouse button. Note, the **yellow color** indicates which is/are the **current object**(s) so if you want to scale the current object you don't need to select ***Pick*** then ***Objects***, you just go directly to select ***Xform*** then ***Scale Uniform or Scale Non-Uniform***.

Activity 6 - Pick nothing

Activity 7 - Move the camera

To move the camera, click and hold the **middle** mouse button in any of the views (top, front, side or perspective). **Drag** the mouse to indicate the direction. To **finish** just release the mouse button. To **zoom in** or **out** just click and hold the **left and middle** mouse button and drag it up(in) or down(out).

Activity 8 - Rotate the camera

To rotate the camera, click and hold the **left** mouse button in the perspective view. **Drag** the mouse to indicate the direction. To finish just release the mouse button.

Activity 9 - See wire frame object

Go to the view where the object appears shaded, click and hold the right mouse button and choose ***Shaded*** to de-activate it.

Activity 10 -Delete the object

To delete one or more objects, first select ***Pick*** then ***Nothing*** to clear all objects from being selected, then select ***Pick*** again with the ***Objects*** option. Now click on the object or objects you want to delete. Then press the ***Delete*** button.

Activity 11 -Create a long rectangle

Now change the length of the line you create in the right view to be longer and repeat the above example. You will get a **long rectangle**.

Activity 12 -Delete the object

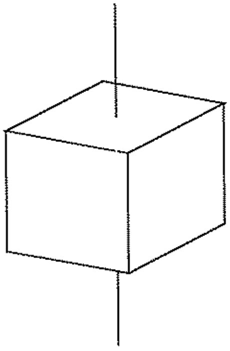
2. *Creating an object by revolution*

Revolution means that an outlined 2D shape is revolved (i.e. turned round) a certain number of degrees until it reaches the beginning to form a 3D solid. This revolution occurs around an imaginary axis which in I3DM's case is defined by the position of a point called "pivot" which by default is on the centre of the grid.

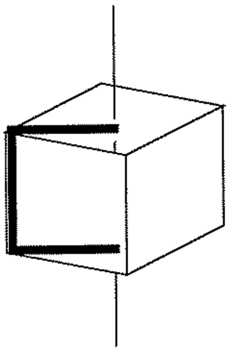
The default **number of segments** is 24 (i.e. the object is formed by 24 "slices"). To change it just type ***seg*** followed by the number of segments you want your object to have **before** you press **Return**.

The **default angle** is 360 (total revolution, i.e. one whole revolution), but you can change it by typing ***angle*** followed by the angle you want your object to have.

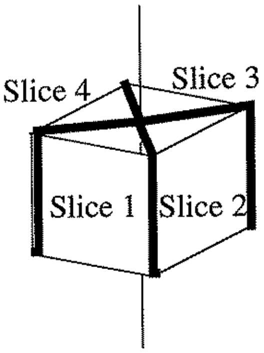
For example, if you want to create a cube the imaginary axis would be:



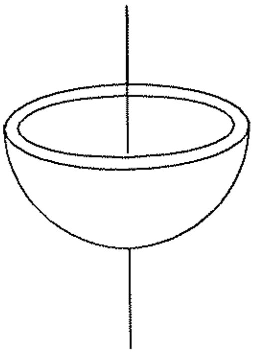
the outline would be:



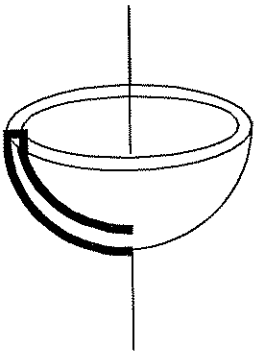
and the number of segments (slices) would be 4:



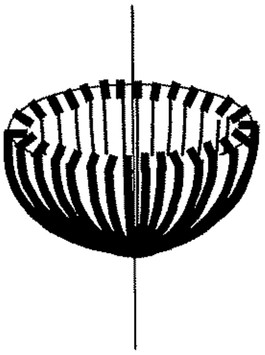
If you wanted to create a fruit bowl the imaginary axis would be:



the outline would be:

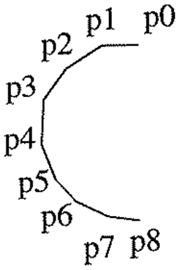


and the higher the number of segments (slices) the smoother the bowl would be:



Activity 13 -Create a sphere

Follow the same instructions to create the following outline as for "Creating an object by extrusion" but instead of clicking back on the first point of the outline to **finish** double click on the last point, leaving the outline with an opening between the last and first points (draw in front view). Note, the point numbers don't appear:

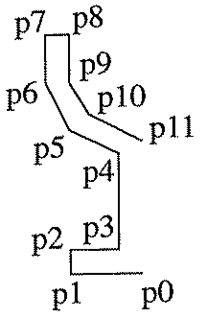


Now to revolve it you need first to move the "pivot" point to where the first or last point is. To do so choose ***Move pivot*** under ***Xform***. A green cross will appear in the centre of the screen, to move it just click and hold the mouse button anywhere in the black screens and move the mouse until you get the cross on top of the first (p0) or last point (p8). Next choose the ***Surface*** menu then ***Revolve*** then ***Revolve Z*** (because we are in the front view) and press **Return**. A 3D object is now created through revolution.

Activity 14 -Delete the object

Activity 15 -Create a wine glass (hollow object) through revolution

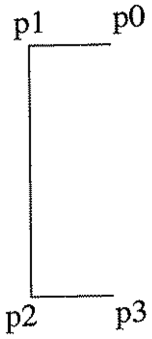
Follow the instructions given for activity 12 with the following outline. Note: the point numbers don't appear.



Activity 16 -Delete the object

Activity 17 -Create a long rectangle

Now follow the same instructions to create the outline as for the above example to create the following outline. Note, the point numbers don't appear.



Again follow the same instructions and place the "pivot" on top of the first or last point and choose ***Revolve Z*** but **before** you press **Return** type ***SEG 4***. You will end up with a **long rectangle**.

Activity 18 -Duplicate the object

To duplicate an object, first select ***Pick*** then ***Nothing*** to clear all objects from being selected, then select ***Pick*** again with the

Objects option. Now click on the object or objects you want to duplicate. Select ***Xform*** then ***Copy Object***, the new object(s) will appear in yellow (current object) next to the original one.

Activity 19 -Connect two objects

To connect one or more objects, first select ***Pick*** then ***Nothing*** to clear all objects from being selected, then select ***Pick*** again with the ***Objects*** option. Now click on the object or objects you want to connect. Select ***Edit*** then ***Group***. Now all objects selected are connected.

Activity 20 -Disconnect the objects

To disconnect one or more objects, first select ***Pick*** then ***Nothing*** to clear all objects from being selected, then select ***Pick*** again with the ***Objects*** option. Now click on the object or objects you want to disconnect. Select ***Edit*** then ***Ungroup***. Now all objects selected are disconnected.

Activity 21 -Delete one of the objects

Activity 22 -Reshape one of the objects

To reshape an object you move its vertices. To do so first select ***Pick*** then ***Nothing*** to clear all objects or vertices from being selected, then select ***Pick*** again with the ***Vertex*** option. Now click on the vertex or vertices you want to move (points represented by crosses). Select ***Xform*** then ***Move*** or ***Rotate*** as desired. **Click and drag** the mouse up/down/left or right and the vertex/vertices will move accordingly. To finish just **release** the mouse button.

Swivel3D

Tutorial

Please follow the tutorial the best you can, it is important you understand all the actions explained in it, you will need them later on.

Note: Throughout this tutorial the term **vertex** means an intersection point between two or more lines in a mesh that represents an object or any corner point that forms an object.

How to create an object in Swivel3D:

There are 2 ways in which to create an object in Swivel3D:

- by extrusion or
- by revolution.

1. Creating an object by extrusion

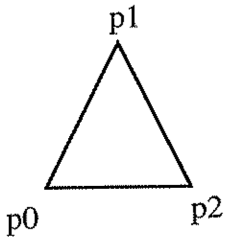
Extrusion means that an outlined 2D shape is extruded (i.e. pushed back) a certain distance to form a 3D solid.

Activity 1 - Create an extruded triangle

Select the ***Object*** menu then ***Design New Object*** a new screen will appear called **editing screen**. Now you are presented with 4 views of the new object (object, cross section, side section and top section).

Note: You don't need to delete the outline in any of the views before you start drawing your own, the old outline will automatically disappear when the new one is finished.

Select the polygon drawing icon which will become black then use the mouse button to draw the following 2D outline in the **cross section**. To **draw** the outline click and release the mouse button where you want your outline to start (p0). You will see that a line now will follow the cursor from the first point. Click and release the mouse again where you want the second point to be and so on until your outline is complete. To **finish** the outline just close it by double-clicking back on the first point (p0). Note, the point numbers don't appear:



Now **extrude** the object by selecting the rectangle icon and using the mouse draw on the **side section** a rectangle as long as you want the object to be extruded.

Now go back to world by clicking on the square on the top left side of the window.

Activity 2 - Move the object

Select the object move **icon** then click and hold the mouse button on the object you want to move. **Drag** the mouse up/down/left or right and the object will move accordingly. To finish just **release** the mouse button. To move the object in or out select the in/out icon then click, hold the mouse button and drag the mouse up(in) or down(out). Note, flashing indicates which is the **current object**.

Activity 3 - Rotate the object

To rotate an object around the Y axis, first **select** the object rotate y **icon** then click and hold the mouse button on the object you want to rotate. **Drag** the mouse right or left and the object will rotate accordingly. To finish just **release** the mouse button. To rotate the object around the x axis select the rotate x icon then click and hold the mouse button and drag the mouse up or down. To rotate the object around the z axis select the rotate z icon then click and hold the mouse button and drag the mouse left or right. Note, flashing indicates which is the current object.

Activity 4 - Display object as wire frame

Select the ***Render*** menu then ***Hidden Line***.

Activity 5 - Scale the object

Select the object scale **icon** then click and hold the mouse button on the object you want to scale. **Drag** the mouse away from you if you want to make the object smaller or towards you to make it bigger. To finish just **release** the mouse button. Note, flashing indicates which is the current object.

Activity 6 - Move the world

First choose ***World*** from the menu then ***World View*** then the view you want: ***Front, Back, Left, Right, Top*** or ***Bottom.***

To **zoom in** select the zoom in icon then click, hold and drag the mouse to form a square selection on the area of the screen you want to zoom in. To **zoom out** select the zoom out icon then click, hold and drag the mouse to form a square selection on the area of the screen you want to zoom out.

Activity 7 - Shade object

Select the ***Render*** menu then ***Shade***.

Activity 8 - Create a long rectangle

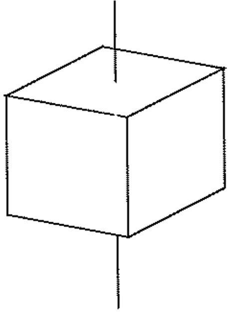
Now double-click on the object, you will get back to the editing screen. Change its **cross section** to a square. You can do this by selecting the rectangle icon and clicking in the cross section. Now go back to the world.

2. *Creating an object by revolution*

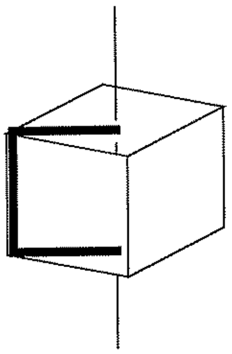
Revolution means that an outlined 2D shape is revolved (i.e. turned round) an imaginary axis a certain number of times until it reaches the beginning to form a 3D solid.

The **number of segments** (i.e. number of slices that form the object) depends on the numbers of points that form the circle in the cross section (the default is 24).

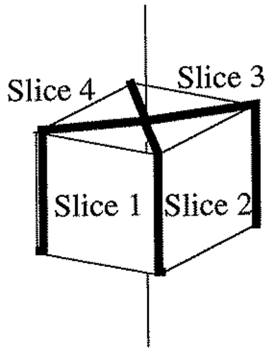
For example, if you want to create a cube the imaginary axis would be:



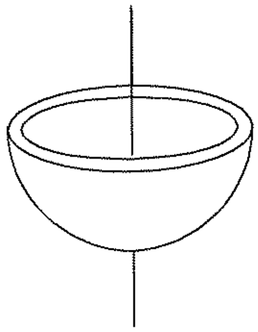
the outline would be:



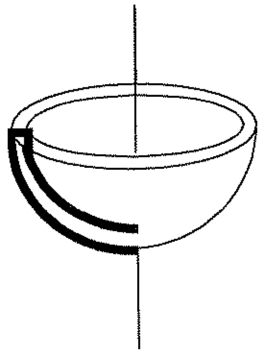
and the number of segments (slices) would be 4:



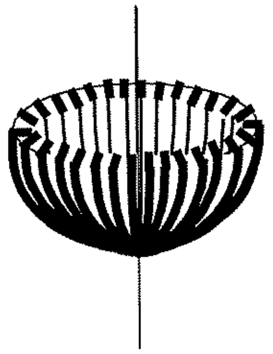
If you wanted to create a fruit bowl the imaginary axis would be:



the outline would be:



and the higher the number of segments (slices) the smoother the bowl would be:

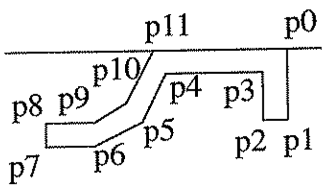


Activity 9 - Create an oblong by revolution

Double-click on the object, you will get back to the editing screen. Select the oval icon ⬭ and click on the **cross section**, a circle will appear. Select the oval icon ⬭ again, click, hold and drag the mouse button in the **side section** to form an elongated circle. Go back to the world and you have an oblong.

Activity 10 -Create a wine glass (hollow object) through revolution

Follow the instructions given for activity 9 with the following outline in the **side section** using the polygon icon ⬠ to create it. Note: the numbers don't appear.



Activity 11 -Change the default number of segments

Double-click on the object, you will get back to the editing screen. Now double-click the oval icon and select *6 Sides* and press *OK*. Click again on the **cross section** to produce a new sphere. Go back to the world. Note: if you need a number of segments that is not available in the default list you can move the points in the sphere (see *Activity 14 - Reshape one of the objects*) over other points (i.e. decreasing them) or by drawing a free hand sphere using the polygon icon (see *Activity 14 - Reshape one of the objects*).

Activity 12 -Duplicate the object

Select the *Edit* menu then *Duplicate* and the current (flashing) object will be **duplicated**. The new object will appear next to the original one.

Activity 13 -Connect two objects

There are 3 ways in which to connect 2 objects in Swivel3D:

- free link;
- lock link and
- ball joint link.

1. *Free link connection*

On a free link connection the child object is free to move independently of the parent, i.e. if the **parent moves** both **child and parent will move** but if the **child moves** just the **child will move**.

2. Lock link connection

On a lock link connection the parent and child are locked together, i.e. they **move and rotate together**.

3. Ball joint connection

On a ball joint connection both parent and child are **lock in position** but both can **rotate independently**.

To connect 2 object using any of the links just select the appropriate icon, **click and hold** on the object to be the child then **drag** the mouse and release it on top of the object to be the parent. Both object will **flash** indicating that the connection is done.

Activity 14 -Disconnect the objects

Select the disconnect **icon** and **click** on the **object** to be **disconnected**, the object will **flash** indicating that the connection is broken.

Activity 15 -Delete one of the objects

Press *Delete* and the current (**flashing**) object will be deleted.

Activity 16 -Reshape one of the objects

Double-click on the object, you will get back to the editing screen. You can reshape an object by changing its shape on the **cross, side or top section**. To change the shape in any of the sections you can either select the polygon , oval or rectangle icon and draw a **new shape or move** existing points around.

There are two icons that allow you to move points, the first, split arrow icon ,
allows you to move points in a **symmetric** way (i.e. move points above and bellow the symmetry line together) on the side and top section simultaneously. If you don't want the **side and top** section to change **simultaneously** then double-click on the split arrow icon and change its behavior.

The second icon, solid arrow icon ,
allows you to move points in a **asymmetric** way (i.e. just move points above or just bellow the symmetry line but not together).

Move object up/down/left/right

Move object in/out/left/right

Rotate object around y axis

Rotate object around x axis

Rotate object around z axis

Scale object

Create cube

Create extruded triangle

Free link objects

Lock link objects

Ball joint link objects

Disconnect objects

Zoom in camera

Zoom out camera

Move point symmetrically

Move point asymmetrically

Polygon drawing

Oval drawing

Rectangle drawing

Appendix V Experiment Questionnaires

Questionnaire

Please spend time "getting into" each question, before writing your answer.

Always put a number in each answer box . Each box must contain the ranking 1, 2, or 3, and none of these should be repeated.

1. You are parting from your best friend. Rank the following in order according to what you might say to him/her. (1 = most likely, 3 = least likely).

I might say...	Rank each answer: 1= most likely, 2 = next most likely, 3 = least likely
"Let's talk again soon."	
"Let's see each other again soon."	
"Let's do something together again soon."	

2. Rank the following situations where 1 is the worst, 3 is the least bad?

For me the worst is ...	Rank each answer: 1= worst, 2 = next worst, 3 = least bad
Being somewhere where there is a noise that is unpleasant for me.	
Being somewhere that I find physically uncomfortable.	
Being somewhere that looks ugly to me.	

3. You are thinking of your best friend. Rank the following in order that is most likely to correspond to your thoughts (1=most likely, 3=least likely)?

The way I would think of my friend is...	Rank each answer: 1= most likely, 2 = next most likely, 3 = least likely
I mentally hear the voice and laughter of my friend.	
I feel as if my friend's presence is close to me.	
I see my friend's appearance.	

4. You are with someone who is complaining that they are having a great deal of trouble solving a certain problem. Rank the following in order corresponding to the one that you would be most likely to say. (1=most likely, 3 = least likely).

I would say ...	Rank each answer: 1= most likely, 2 = next most likely, 3 = least likely
"Try to see your way through the problem."	
"Try to get a grip on the problem."	
"Try to talk your way through the problem."	

5. Which of the following is most important to you in judging a film (movie)? Rank in the order 1 (most important) to 3 (least important).

The most important to me is ...	Rank each answer: 1= most likely, 2 = next most likely, 3 = least likely
The feelings and emotions.	
The visual imagery.	
The dialogue and sound play.	

6. You are trying to get to sleep in bed. Rank the following in order so that, if any of these conditions occurred, would be the one most likely to prevent you from getting to sleep. (1= most likely to prevent you sleeping, 3=least likely).

The one most likely to prevent me from sleeping is ...	Rank each answer: 1= most likely to prevent me from sleeping, 2 = next most likely, 3 = least likely
Bread crumbs have got into the bed and my night clothes.	
Some neighbours are playing loud and unpleasant music.	
There is a bright flashing light shining into my bedroom, even through the curtains, that I can see even with my eyes closed.	

7. You are by the ocean, and it is safe and warm enough to go into the water. Which of the following would be most likely to entice you to go into the water? Rank in order (1= most enticing, 3=least enticing).

The one most likely entice me into the water is ...	Rank each answer: 1= most likely to entice me into the water, 2 = next most likely, 3 = least likely
The sea looks particularly beautiful, I notice the highlights where the sea glistens in the bright sun.	
I can sense how my body will feel in the water.	
I can hear the gentle sounds of the waves and the sounds of others playing in the sea.	

8. Suppose that you are soon going to give a talk in front of an audience - eg, as part of a job interview, a presentation, or whatever. *You are technically well-prepared for the talk.* Which of the following are you most likely to be experiencing? (Rank in order 1 to 3, 1=most likely, 3 = least likely).

The one I am most likely to be experiencing is ...	Rank 1= most likely 2 = next most likely, 3 = least likely
I am saying the talk to myself over and over again in my mind.	
I am picturing the occasion, seeing the audience, the environment, etc..	
I am feeling the emotions and physical sensations I will have during the occasion.	

9. Suppose over the next month you had to choose only *one* of the following activities (the other two would be banned). Rank them in the order that you would be most likely to choose. (1=most likely to choose, 3=least likely).

The one I am most likely to choose to continue is ...	Rank 1= most likely to choose, 2 = next most likely, 3 = least likely
Doing my favourite sport or dancing.	
Hearing my favourite music.	
Seeing my favourite scenery.	

10. Think of a pleasant location that you have visited, *and where you would like to be now.* When you think about this, which of the following is most prominent in your way of thinking about this location? Rank the possible answers in order.

When I think about the location, the most prominent thoughts are..	Rank 1= most prominent, 2 = least prominent 3 = least prominent
The visual images of the place	
The feelings associated with being in that place	
The sounds that I would hear in that place	

THANK YOU FOR YOUR COOPERATION!

Questionnaire 1A

Package ____________ Subject Number ________

Please answer this questionnaire as fully as possible.
Where multiple choices are given, please tick ONLY ONE of them.
If you make a mistake just cross over it and write the correct answer next to it.

About yourself

1. **Are you male or female ?**

male	
female	

2. **Are you right or left handed ?**

right-handed	
left-handed	

3. **Please specify, next to the corresponding Faculty(ies)/School(s), which course(s) (complete or incomplete) you have taken on a graduate and post-graduate level (please indicate if BSc, MSc, PhD or other) :**

Science ______________________________

Engineering ______________________________

Arts ______________________________

Medicine ______________________________

4. **Have you had any training in technical drawing ?**

No	
Yes	

5. **Please state at least one and not more than five of your hobbies (i.e. any sports, games, arts and crafts, etc.) :**

i) ______________________________

ii) ______________________________

iii) ______________________________

iv) ______________________________

v) ______________________________

6. **Have you used the ____________________ package before ? If not, please go to question 8.**

No	
Yes	

7. **If yes to question 6, please rate your level of expertise :**

1. novice	
2. ⋮	
3. ⋮	
4. ⋮	
5. ⋮	
6. ⋮	
7. expert	

8. **Have you used any Computer Aided Design (CAD) package before ? If not, please go to question 10.**

No	
Yes	

9. **If yes to question 8, please rate your level of expertise :**

1. novice	
2. ⋮	
3. ⋮	
4. ⋮	
5. ⋮	
6. ⋮	
7. expert	

10. **Have you used a ______________________ before ? If not, please go to question 12.**

No	
Yes	

11. **If yes to question 10, please state how often do you use a ____________________ ?**

I use a ______________________

1. daily	
2. weekly	
3. monthly	
4. other	

.

12. **How often do you use computers ?**

1. not at all	
2. ⋮	
3. ⋮	
4. ⋮	
5. ⋮	
6. ⋮	
7. very often	

Questionnaire 2A

Package ______________ Subject Number ________

Please answer this questionnaire as fully as possible.

Where multiple choices are given, please tick ONLY ONE of them.

If you make a mistake just cross over it and write the correct answer next to it.

About the objects you created

Task 1 : ______________________

1. **Describe in not more than 4 short statements how you intend to create the object on task 1:**

   i) ______________________

   ii) ______________________

   iii) ______________________

   iv) ______________________

2. **What was the most difficult aspect of task 1 ?**

The most difficult aspect of task 1 was ______________________________

____

____

3. **How difficult would you rate the aspect given in question 2 ?**

I would rate the aspect given in question 1 as being

1. not at all	
2. ⋮	
3. ⋮	
4. ⋮	
5. ⋮	
6. ⋮	
7. very	

difficult.

4. **Are you satisfied with the final result of your work on task 1 ?**

I am

1. not at all	
2. ⋮	
3. ⋮	
4. ⋮	
5. ⋮	
6. ⋮	
7. very	

satisfied with the final result of my work on task 1.

5. **How would you rate the <u>overall</u> level of difficulty of task 1 ?**

I found the <u>overall</u> level of difficulty of task 1 to be

1. very easy	
2. ⋮	
3. ⋮	
4. ⋮	
5. ⋮	
6. ⋮	
7. very difficult	

.

Task 2 : ______________________________

6. **Describe in not more than 4 short statements how you intend to create the object on task 2 :**

i) ______________________________

ii) ______________________________

iii) ______________________________

iv) ______________________________

7. **What was the most difficult aspect of task 2 ?**

The most difficult aspect of task 2 was ____

____

____

8. **How difficult would you rate the aspect given in question 7 ?**

I would rate the aspect given in question 2 as being … *difficult.*

1. not at all	
2. ⋮	
3. ⋮	
4. ⋮	
5. ⋮	
6. ⋮	
7. very	

9. **Are you satisfied with the final result of your work on task 2 ?**

I am … *satisfied with the final result of my work on task 2.*

1. not at all	
2. ⋮	
3. ⋮	
4. ⋮	
5. ⋮	
6. ⋮	
7. very	

10. **How would you rate the <u>overall</u> level of difficulty of task 2 ?**

I found the <u>overall</u> level of difficulty of task 2 to be … .

1. very easy	
2. ⋮	
3. ⋮	
4. ⋮	
5. ⋮	
6. ⋮	
7. very difficult	

Task 3 : ______________________

11. **Describe in not more than 4 short statements how you intend to create the object on task 3 :**

i) ______________________

ii) ______________________

iii) ______________________

iv) ______________________

12. What was the most difficult aspect of task 3 ?

The most difficult aspect of task 3 was ________________________________

____

____

13. How difficult would you rate the aspect given in question 12 ?

I would rate the aspect given in question 3 as being *difficult.*

1. not at all	
2. ⋮	
3. ⋮	
4. ⋮	
5. ⋮	
6. ⋮	
7. very	

14. Are you satisfied with the final result of your work on task 3 ?

I am *satisfied with the final result of my work on task 3.*

1. not at all	
2. ⋮	
3. ⋮	
4. ⋮	
5. ⋮	
6. ⋮	
7. very	

15. How would you rate the <u>overall</u> level of difficulty of task 3 ?

I found the <u>overall</u> level of difficulty of task 3 to be .

1. very easy	
2. ⋮	
3. ⋮	
4. ⋮	
5. ⋮	
6. ⋮	
7. very difficult	

Task 4 : ______________________________

16. **Describe in not more than 4 short statements how you intend to create the object on task 4 :**

i) ______________________________

ii) ______________________________

iii) ______________________________

iv) ______________________________

17. What was the most difficult aspect of task 4 ?

The most difficult aspect of task 4 was ______________________________

____

____

18. How difficult would you rate the aspect given in question 17 ?

I would rate the aspect given in question 4 as being

1. not at all	
2. ⋮	
3. ⋮	
4. ⋮	
5. ⋮	
6. ⋮	
7. very	

difficult.

19. Are you satisfied with the final result of your work on task 4 ?

I am

1. not at all	
2. ⋮	
3. ⋮	
4. ⋮	
5. ⋮	
6. ⋮	
7. very	

satisfied with the final result of my work on task 4.

20. How would you rate the <u>overall</u> level of difficulty of task 4 ?

I found the <u>overall</u> level of difficulty of task 4 to be

1. very easy	
2. ⋮	
3. ⋮	
4. ⋮	
5. ⋮	
6. ⋮	
7. very difficult	

.

Task 5 : ____________________

21. **Describe in not more than 4 short statements how you intend to create the object on task 5 :**

    i) ____________________

    ii) ____________________

    iii) ____________________

    iv) ____________________

22. What was the most difficult aspect of task 5 ?

The most difficult aspect of task 5 was ____

____

____

23. How difficult would you rate the aspect given in question 22 ?

I would rate the aspect given in question 5 as being … *difficult.*

1. not at all	
2. ⋮	
3. ⋮	
4. ⋮	
5. ⋮	
6. ⋮	
7. very	

24. Are you satisfied with the final result of your work on task 5 ?

I am … *satisfied with the final result of my work on task 5.*

1. not at all	
2. ⋮	
3. ⋮	
4. ⋮	
5. ⋮	
6. ⋮	
7. very	

25. How would you rate the <u>overall</u> level of difficulty of task 5 ?

I found the <u>overall</u> level of difficulty of task 5 to be … .

1. very easy	
2. ⋮	
3. ⋮	
4. ⋮	
5. ⋮	
6. ⋮	
7. very difficult	

Task 6 : ______________________

26. **Describe in not more than 4 short statements how you intend to create the object on task 6 :**

i) ______________________

ii) ______________________

iii) ______________________

iv) ______________________

27. What was the most difficult aspect of task 6 ?

The most difficult aspect of task 6 was ______________________________

____

____

28. How difficult would you rate the aspect given in question 27 ?

I would rate the aspect given in question 6 as being *difficult.*

1. not at all	
2. ⋮	
3. ⋮	
4. ⋮	
5. ⋮	
6. ⋮	
7. very	

29. Are you satisfied with the final result of your work on task 6 ?

I am *satisfied with the final result of my work on task 6.*

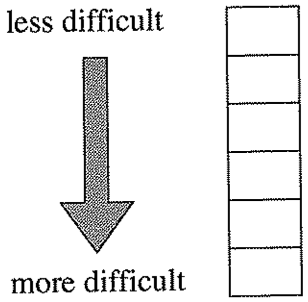
1. not at all	
2. ⋮	
3. ⋮	
4. ⋮	
5. ⋮	
6. ⋮	
7. very	

30. How would you rate the <u>overall</u> level of difficulty of task 6 ?

I found the <u>overall</u> level of difficulty of task 6 to be .

1. very easy	
2. ⋮	
3. ⋮	
4. ⋮	
5. ⋮	
6. ⋮	
7. very difficult	

31. Now that you completed all tasks please order them in increasing order of difficulty :



Questionnaire 3A

Package ____________ Subject Number ________

Please answer this questionnaire as fully as possible.
Where multiple choices are given, please tick ONLY ONE of them.
If you make a mistake just cross over it and write the correct answer next to it.

About the package you used

1. **Now that you finished all the tasks, how satisfied are you with the work you performed?**

I am

1. not at all	
2. ⋮	
3. ⋮	
4. ⋮	
5. ⋮	
6. ⋮	
7. very	

satisfied with the work I performed.

2. **And how satisfied are you with the package you used ?**

I am

1. not at all	
2. ⋮	
3. ⋮	
4. ⋮	
5. ⋮	
6. ⋮	
7. very	

satisfied with the package I used.

3. How easy was it for you to locate the tools you needed ?

It was

1. very easy	
2. ⋮	
3. ⋮	
4. ⋮	
5. ⋮	
6. ⋮	
7. very difficult	

for me to locate the tools I needed.

4. How easy was it for you to use the tools you needed ?

It was

1. very easy	
2. ⋮	
3. ⋮	
4. ⋮	
5. ⋮	
6. ⋮	
7. very difficult	

for me to use the tools I needed.

5. Amongst the features you used which one did you find:

- most useful ? ____

Why ?

____

____

- least useful ? ____

Why ?

____

____

6. **From the list below please tick 5 words which most remind you of the package you used.**

- adapting ☐

- altering ☐

- constructing ☐

- designing ☐

manufacturing ☐

- outlining ☐

- sketching ☐

- engraving ☐

- assembling ☐

- copying ☐

- drawing ☐

merging ☐

- painting ☐

- tracing ☐

- adjusting ☐

- building ☐

- crafting ☐

- modelling ☐

- sculpting ☐

7. **For each of the tasks you performed, please state any additional tools you would like the package to have :**

Task 1 - ____________________

Task 2 - ____________________

Task 3 - ____________________

Task 4 - ____________________

Task 5 - ____________________

Task 6 - ____________________

8. **Please write below any suggestions or comments you wish to make about the package you used.**

9. **Please write below any suggestions or comments you wish to make about the experiment.**

Thank you for taking part in this experiment and helping me with my research.

Shancy Kou - Department of Computer Science.

Appendix VI Experiment Observer's Sheet

Package Subject Number ______

Start	Tut.	Q1	T1	Q2	T2	Q3	T3

T1 : ______

Revolution		
One object		
Forces		
Cut		
Extrusion		

Connected		
Move vertices		
As faces		
Num. objects		
Right		

T2 : ______

Revolution		
One object		
Forces		
Cut		
Extrusion		

Connected		
Move vertices		
As faces		
Num. objects		
Right		

T3 : ______

Revolution		
One object		
Forces		
Cut		
Extrusion		

Connected		
Move vertices		
As faces		
Num. objects		
Right		

Package Subject Number ______

Q4	T4	Q5	T5	Q6	T6	End

T4 : ______________________

Revolution		
One object		
Forces		
Cut		
Extrusion		

Connected		
Move vertices		
As faces		
Num. objects		
Right		

T5 : ______________________

Revolution		
One object		
Forces		
Cut		
Extrusion		

Connected		
Move vertices		
As faces		
Num. objects		
Right		

T6 : ______________________

Revolution		
One object		
Forces		
Cut		
Extrusion		

Connected		
Move vertices		
As faces		
Num. objects		
Right		

Appendix VII Detailed Raw Data per Package

VII.1 Frequency tables

Age

	18 (%)	19 (%)	20 (%)	21-23 (%)	24-47 (%)
IDM	10	40	10	10	30
IM	20	20	30	20	10
I3DM	10	10	40	20	20
Swivel3D	20	30	0	30	20
Total	15	25	20	20	20

Spatial Ability Score

	41-58 (%)	59-66 (%)	67-72 (%)	73-80 (%)
IDM	20	30	20	30
IM	20	30	30	20
I3DM	30	20	20	30
Swivel3D	20	20	30	30
Total	22.5	25	25	27.5

Number of Visual Answers in the VAK Questionnaire

	1-2 (%)	3-4 (%)	5-6 (%)
IDM	40	50	10
IM	40	20	30
I3DM	40	20	30
Swivel3D	20	40	30
Total	37.8	35.1	27

Number of Auditory Answers in the VAK Questionnaire

	1-2 (%)	3-4 (%)	5-7 (%)
IDM	10	50	40
IM	20	40	30
I3DM	30	60	10
Swivel3D	20	60	10
Total	21.1	55.3	23.7

Number of Kinaesthetic Answers in the VAK Questionnaire

	1-2 (%)	3-4 (%)	5-6 (%)
IDM	20	40	30
IM	40	40	10
I3DM	20	40	40
Swivel3D	40	30	20
Total	32.4	40.5	27

Gender

	Female (%)	Male (%)
IDM	60	40
IM	40	60
I3DM	50	50
Swivel3D	50	50
Total	50	50

Handedness

	Right (%)	Left (%)
IDM	60	40
IM	100	0
I3DM	90	10
Swivel3D	80	20
Total	82.5	17.5

Previous Technical Drawing Experience

	No (%)	Yes (%)
IDM	60	40
IM	70	30
I3DM	80	20
Swivel3D	70	30
Total	70	30

Previous CAD Experience

	No (%)	Yes (%)
IDM	100	0
IM	70	30
I3DM	80	20
Swivel3D	80	20
Total	82.5	17.5

Used Machine Before

	No (%)	Yes (%)
IDM	100	0
IM	100	0
I3DM	100	0
Swivel3D	50	50
Total	87.5	12.5

Problems with the Mouse in Silicon Graphics Machine

	No (%)	Yes (%)
IDM	40	60
IM	50	50
I3DM	20	80
Total	36.7	63.3

VII.2 Mean and standard deviation table

	IDM	IM	I3DM	Swivel3D
Age	22 ± 5	20 ± 2	23 ± 7	23 ± 9
Spatial ability score	66 ± 12	65 ± 8	67 ± 10	67 ± 10
Num. of visual answers VAK	3 ± 2	3 ± 2	3 ± 2	3 ± 2
Num. of auditory answers	4 ± 1	3 ± 2	3 ± 1	3 ± 2
Num. of kinaesthetic answers	3 ± 2	3 ± 2	4 ± 2	3 ± 2
Computer experience (1 to 7)	5 ± 2	5 ± 2	4 ± 2	5 ± 2
Duration of experiment (min)	138 ± 20	144 ± 21	167 ± 23	175 ± 45
Time executing tutorial (min)	39 ± 6	36 ± 8	47 ± 10	41 ± 11
Think about primitive object	69 ± 34	88 ± 61	87 ± 57	117 ± 57
Think about cut object	70 ± 38	82 ± 84	135 ± 128	119 ± 128
Think about abstract object	58 ± 33	75 ± 37	101 ± 50	137 ± 207
Think about revolution object	63 ± 57	74 ± 38	42 ± 13	61 ± 34
Think about composite object	83 ± 50	81 ± 36	73 ± 28	74 ± 32
Think about general object	89 ± 80	82 ± 87	157 ± 146	114 ± 146
Think about all objects	72 ± 29	81 ± 31	99 ± 48	104 ± 91
Satisf. with primitive object	6 ± 1	6 ± 1	6 ± 1	6 ± 1
Satisf. with cut object	5 ± 1	5 ± 2	3 ± 2	2 ± 1
Satisf. with abstract object	4 ± 2	6 ± 1	5 ± 2	5 ± 2
Satisf. with revolution object	5 ± 1	6 ± 1	5 ± 2	6 ± 2
Satisf. with composite object	4 ± 1	5 ± 2	5 ± 1	5 ± 1
Satisf. with general object	4 ± 1	5 ± 2	4 ± 2	5 ± 2
Satisf. all objects combined	5 ± 1	5 ± 1	5 ± 1	5 ± 1
Satisf. with work performed	5 ± 1	5 ± 1	5 ± 1	5 ± 2
Satisf. with application	5 ± 1	6 ± 1	5 ± 1	6 ± 1
Ease to locate tools	2 ± 2	2 ± 1	4 ± 1	2 ± 1
Ease to use tools	3 ± 1	2 ± 1	3 ± 1	3 ± 1

Appendix VIII Linear Regression Analysis of Geometrical Applications

For an introduction on linear regression analysis please refer to Section 6.2 on page 95.

INDEX TO INDEPENDENT VARIABLES:

AGE: subject's age

BEF(1): subject hasn't used machine before

BEF(2): subject has used machine before

CPKG: previous CAD experience

COMP: previous computer experience

DUR: duration of whole experiment

EUSE: tools ease of use

F: number of kinaesthetic answers in the VAK questionnaire

GRP(1): arts subjects

GRP(2): sciences subjects

HAND(1): right-handed

HAND(2): left-handed

MOUS(1): subject didn't have any problem with mouse

MOUS(2): subject had problem with mouse

PKG(1): Interactive 3D Modeller (I3DM)

PKG(2): Interactive Modeller (IM), built by author, without forces

PKG(3): Swivel3D

Q1: time to think about how to execute primitive object

Q2: time to think about how to execute cut object

Q3: time to think about how to execute abstract object

Q4: time to think about how to execute revolution object

Q5: time to think about how to execute composite object

Q6: time to think about how to execute general object

S: number of auditory answers in the VAK questionnaire

SATI: level of satisfaction with package

SATW: level of satisfaction with overall work

SCOR: spatial ability score

SEX(1): female

SEX(2): male

T1: time to execute primitive object

T1SA: level of satisfaction with resulting primitive object

T2: time to execute cut object

T2EN(1): subject finished building cut object

T2EN(2): subject gave up building cut object

T2EN(3): time was up for building cut object

T2SA: level of satisfaction with resulting cut object

T3: time to execute abstract object

T3EN(1): subject finished building abstract object

T3EN(2): subject gave up building abstract object

T3EN(3): time was up for building abstract object

T3RI(1): subject didn't produced right abstract object

T3RI(2): subject would have produced right abstract object if time wasn't up

T3RI(3): subject produced right abstract object

T3SA: level of satisfaction with resulting abstract object

T4: time to execute revolution object

T4SA: level of satisfaction with resulting revolution object

T5: time to execute composite object

T5RI(1): subject didn't produced right composite object

T5RI(2): subject would have produced right composite object if time wasn't up

T5RI(3): subject produced right composite object

T6: time to execute general object

T6SA: level of satisfaction with resulting general object

TECH(1): with no previous technical drawing experience

TECH(2): with previous technical drawing experience

TUT: time spent going through tutorial

V: number of visual answers in the VAK questionnaire

The column labelled "estimate" represents the regression coefficients whereas "parameter" gives the independent variable.

Regression analysis assumes constant variance and statistical independence between the cases. Standard residual plots of residual error against fitted values do not contradict these assumptions.

Table 16 - Regression of satisfaction with resulting cut object (t2sa)

	estimate	s.e.	parameter
1	4.739	0.6624	CONSTANT
2	1.166	0.6731	PKG(2)
3	-0.6898	0.6832	PKG(3)
4	-0.002193	0.0006644	T2

correlation = 0.5133

Table 17 - Regression of execution time for primitive object (t1)

	estimate	s.e.	parameter
1	425.2	209.0	CONSTANT
2	867.9	548.3	PKG(2)
3	-626.0	253.3	PKG(3)
4	2.270	0.5755	Q1
5	-13.01	8.313	PKG(1).AGE
6	-64.05	24.69	PKG(2).AGE
7	7.453	6.494	PKG(3).AGE

correlation = 0.5764

Table 18 - Regression of execution time for cut object (t2)

	estimate	s.e.	parameter
1	1718.	461.5	CONSTANT
2	-65.94	144.0	PKG(2)
3	267.3	141.2	PKG(3)
4	2.024	0.5281	Q2
5	-19.38	6.587	SCOR

correlation = 0.569

Table 19 - Regression of thinking time for abstract object (q3)

	estimate	s.e.	parameter
1	273.8	85.25	CONSTANT
2	-44.00	48.70	PKG(2)
3	154.2	60.53	PKG(3)
4	-228.1	72.47	BEF(2)
5	-7.584	3.430	AGE

correlation = 0.341

Table 20 - Regression of execution time for abstract object (t3)

	estimate	s.e.	parameter
1	936.6	101.2	CONSTANT
2	-304.5	104.1	PKG(2)
3	179.4	103.5	PKG(3)
4	296.3	94.27	TECH(2)
5	-43.52	20.82	COMP

correlation = 0.6008

Table 21 - Regression of execution time for all tasks combined (t)

	estimate	s.e.	parameter
1	884.9	190.5	CONSTANT
2	-135.2	54.86	PKG(2)
3	67.51	54.24	PKG(3)
4	0.9433	0.3886	Q
5	-5.278	2.603	SCOR

correlation = 0.5462

Table 22 - Regression of satisfaction with resulting revolution object t4sa)

	estimate	s.e.	parameter
1	5.981	0.5925	CONSTANT
2	1.693	0.7013	PKG(2)
3	0.9490	0.6605	PKG(3)
4	-0.01847	0.009082	Q4

correlation = 0.2149

Table 23 - Regression of satisfaction of all tasks combined (sa)

	estimate	s.e.	parameter
1	3.647	0.5550	CONSTANT
2	0.5382	0.2281	PKG(2)
3	0.2152	0.2256	PKG(3)
4	0.2880	0.08622	SATW
5	-0.004287	0.001789	Q

correlation = 0.6365

Table 24 - Regression of thinking time for the revolution object (q4)

	estimate	s.e.	parameter
1	134.7	39.66	CONSTANT
2	30.57	12.49	PKG(2)
3	19.04	12.47	PKG(3)
4	-1.387	0.5806	SCOR

correlation = 0.3229

Table 25 - Regression of execution time for the general object (t6)

	estimate	s.e.	parameter
1	871.3	97.49	CONSTANT
2	-241.6	137.9	PKG(2)
3	39.60	137.9	PKG(3)

correlation = 0.1529

Table 26 - Regression of execution time for the revolution object (t4)

	estimate	s.e.	parameter
1	618.4	145.6	CONSTANT
2	-6.127	2.153	SCOR
3	-115.4	42.78	TECH(2)

correlation = 0.3387

Table 27 - Regression of execution time for the composite object (t5)

	estimate	s.e.	parameter
1	811.4	74.33	CONSTANT
2	295.0	93.60	GRP(2)
3	-316.8	105.8	TECH(2)

correlation = 0.4517

Table 28 - Regression of satisfaction with resulting primitive object (t1sa)

	estimate	s.e.	parameter
1	5.459	0.4016	CONSTANT
2	-0.001869	0.0007197	T1
3	0.3220	0.09397	S

correlation = 0.4497

Table 29 - Regression of satisfaction with resulting composite object (t5sa)

	estimate	s.e.	parameter
1	6.961	0.5946	CONSTANT
2	-0.002013	0.0006375	T5

correlation = 0.2627

Table 30 - Regression of satisfaction with resulting general object (t6sa)

	estimate	s.e.	parameter
1	6.880	0.7862	CONSTANT
2	-0.008128	0.002382	Q6
3	-0.001977	0.0009506	T6

correlation = 0.4510

Table 31 - Dependent variable: level of satisfaction with package (sati)

	estimate	s.e.	parameter
1	10.22	1.307	CONSTANT
2	0.1245	0.01495	AGE
3	-1.783	2.065	TECH(1).PKG(2)
4	-19.63	2.253	TECH(1).PKG(3)
5	2.707	0.4294	TECH(2).PKG(1)
6	-3.566	1.913	TECH(2).PKG(2)
7	-18.43	2.112	TECH(2).PKG(3)
8	-0.1375	0.08449	PKG(1).S
9	0.02090	0.06670	PKG(2).S
10	0.3356	0.08834	PKG(3).S
11	-0.05830	0.07252	PKG(1).T6SA
12	0.06152	0.07567	PKG(2).T6SA
13	0.9834	0.1264	PKG(3).T6SA
14	-0.04631	0.007801	PKG(1).DUR
15	-0.02744	0.007871	PKG(2).DUR
16	0.03918	0.006063	PKG(3).DUR
17	0.5870	0.2899	PKG(1).GRP(2)
18	-1.691	0.3430	PKG(2).GRP(2)
19	-0.6565	0.2273	PKG(3).GRP(2)

correlation = 0.9516

F(11,11) = 19.64

tabulated value at 0.1% F(11,11) = 7.7

Table 32 - Dependent variable: level of satisfaction with overall work performed (satw)

	estimate	s.e.	parameter
1	-1.952	0.5841	CONSTANT
2	0.09229	0.01452	AGE
3	1.216	0.1506	T1SA.PKG(1)
4	1.099	0.1328	T1SA.PKG(2)
5	0.2900	0.1898	T1SA.PKG(3)
6	-0.8083	0.1705	PKG(1).S
7	-0.3004	0.09234	PKG(2).S
8	-0.02814	0.1075	PKG(3).S
9	-0.1575	0.07417	PKG(1).T6SA
10	-0.05913	0.07482	PKG(2).T6SA
11	0.6738	0.1337	PKG(3).T6SA
12	0.2559	0.08459	PKG(1).V
13	0.01181	0.08297	PKG(2).V
14	-0.08312	0.1096	PKG(3).V

correlation = 0.9383

F(16,16) = 15.22

tabulated value at 0.1% F(16,16) = 5.2

Table 33 - Dependent variable: level of satisfaction with primitive object (t1sa)

	estimate	s.e.	parameter
1	3.194	1.457	CONSTANT
2	0.2790	0.06380	COMP
3	0.2425	0.07547	F
4	0.6982	0.1493	S.PKG(1)
5	0.2525	0.09666	S.PKG(2)
6	-0.1226	0.1699	S.PKG(3)
7	-0.08383	0.5153	PKG(1).TECH(2)
8	5.164	2.574	PKG(2).TECH(1)
9	3.169	2.429	PKG(2).TECH(2)
10	-1.520	2.321	PKG(3).TECH(1)
11	-0.4920	2.490	PKG(3).TECH(2)
12	-0.02195	0.01998	PKG(1).SCOR
13	-0.07210	0.03012	PKG(2).SCOR
14	0.03482	0.02544	PKG(3).SCOR

correlation = 0.8463

F(16,16) = 5.508

tabulated value at 0.1% F(16,16) = 5.2

Table 34 - Dependent variable: level of satisfaction with cut object (t2sa)

	estimate	s.e.	parameter
1	3.048	0.8248	CONSTANT
2	1.612	0.6956	BEF(2)
3	1.020	1.169	T2EN(1).PKG(2)
4	0.8558	1.586	T2EN(1).PKG(3)
5	-1.976	0.7277	T2EN(2).PKG(1)
6	-3.852	1.435	T2EN(2).PKG(2)
7	-0.4280	1.181	T2EN(2).PKG(3)
8	-3.905	1.051	T2EN(3).PKG(1)
9	-3.574	1.614	T2EN(3).PKG(2)
10	0.1582	1.653	T2EN(3).PKG(3)
11	-3.619	0.8248	PKG(1).TECH(2)
12	-0.9925	0.6617	PKG(2).TECH(2)
13	1.185	0.6876	PKG(3).TECH(2)
14	0.5714	0.1602	PKG(1).COMP
15	0.3609	0.1510	PKG(2).COMP
16	-0.4477	0.2153	PKG(3).COMP

correlation = 0.9043

F(14,14) = 9.449

tabulated value at 0.1% F(14,14) = 6.0

Table 35 - Dependent variable: level of satisfaction with abstract object (t3sa)

	estimate	s.e.	parameter
1	6.315	1.860	CONSTANT
2	1.530	0.7967	T3RI(2)
3	3.148	0.4927	T3RI(3)
4	-0.9934	0.3492	PKG(1).T1SA
5	1.146	0.2552	PKG(2).T1SA
6	0.6581	0.3760	PKG(3).T1SA
7	-0.07425	0.6698	PKG(1).TECH(2)
8	-11.15	2.252	PKG(2).TECH(1)
9	-10.44	2.071	PKG(2).TECH(2)
10	-7.484	2.881	PKG(3).TECH(1)
11	-9.304	3.340	PKG(3).TECH(2)
12	0.5887	0.1769	PKG(1).COMP
13	0.1184	0.1178	PKG(2).COMP
14	0.1020	0.1624	PKG(3).COMP

correlation = 0.9228

F(16,16) = 11.95

tabulated value at 0.1% F(16,16) = 5.2

Table 36 - Dependent variable: level of satisfaction with revolution object (t4sa)

	estimate	s.e.	parameter
1	-1.398	1.274	CONSTANT
2	1.423	0.4760	HAND(2)
3	0.07508	0.01730	SCOR
4	-0.1466	0.06875	COMP
5	0.2989	0.1233	PKG(1).T2SA
6	-0.08678	0.08837	PKG(2).T2SA
7	0.9212	0.2162	PKG(3).T2SA
8	2.757	0.5445	PKG(1).GRP(2)
9	4.407	0.8186	PKG(2).GRP(1)
10	3.645	0.9638	PKG(2).GRP(2)
11	0.8041	0.7019	PKG(3).GRP(1)
12	1.935	0.7749	PKG(3).GRP(2)
13	2.579	0.6930	PKG(1).TECH(2)
14	-0.1870	0.5233	PKG(2).TECH(2)
15	-0.8309	0.6683	PKG(3).TECH(2)
16	-1.078	0.5741	PKG(1).SEX(2)
17	-0.03209	0.5154	PKG(2).SEX(2)
18	0.1734	0.6139	PKG(3).SEX(2)

correlation = 0.8591 from 28 observations

F(10,10) = 6.097

tabulated value at 0.5% F(10,10) = 5.847

Table 37 - Dependent variable: level of satisfaction with composite object (t5sa)

	estimate	s.e.	parameter
1	7.647	0.9698	CONSTANT
2	1.450	0.2367	MOUS(2)
3	0.1492	0.04788	F
4	-2.667	0.2909	T5RI(2)
5	-2.043	0.3063	T5RI(3)
6	1.284	2.275	GRP(1).PKG(2)
7	-10.16	1.265	GRP(1).PKG(3)
8	-0.3050	0.2603	GRP(2).PKG(1)
9	0.1022	2.608	GRP(2).PKG(2)
10	-10.55	1.317	GRP(2).PKG(3)
11	0.01101	0.01350	PKG(1).SCOR
12	-0.1465	0.02195	PKG(2).SCOR
13	0.1369	0.01240	PKG(3).SCOR

	estimate	s.e.	parameter
14	-0.1070	0.01905	PKG(1).AGE
15	0.3371	0.06634	PKG(2).AGE
16	0.02548	0.01546	PKG(3).AGE

correlation = 0.9714

F(14,14) = 34.02

tabulated value at 0.1% F(14,14) = 6.0

Table 38 - Dependent variable: level of satisfaction with general object (t6sa)

	estimate	s.e.	parameter
1	6.793	1.763	CONSTANT
2	2.895	0.3625	GRP(2)
3	-0.4434	0.1022	T3SA
4	-15.52	4.868	T6RI(1).PKG(2)
5	-5.680	2.052	T6RI(1).PKG(3)
6	-6.358	1.932	T6RI(2).PKG(1)
7	-12.09	3.779	T6RI(2).PKG(2)
8	-1.887	2.023	T6RI(2).PKG(3)
9	-2.880	1.672	T6RI(3).PKG(1)
10	-17.94	4.324	T6RI(3).PKG(2)
11	-0.1684	1.874	T6RI(3).PKG(3)
12	0.1724	0.3880	PKG(1).T4SA
13	2.533	0.5902	PKG(2).T4SA
14	0.2369	0.1480	PKG(3).T4SA
15	-1.884	2.028	PKG(1).TECH(2)
16	-4.094	0.9262	PKG(2).TECH(2)
17	1.765	0.5571	PKG(3).TECH(2)
18	-0.2610	0.2323	PKG(1).V
19	0.4739	0.1549	PKG(2).V
20	-0.4407	0.1556	PKG(3).V

correlation = 0.9547

F(10,10) = 21.05

tabulated value at 0.1% F(10,10) = 8.754

Table 39 - Dependent variable: easy to locate tools (eloc)

	estimate	s.e.	parameter
1	7.430	1.367	CONSTANT
2	-0.2776	0.05575	COMP
3	-0.5764	0.1197	S.PKG(1)
4	-0.1862	0.08653	S.PKG(2)
5	0.1142	0.1249	S.PKG(3)

	estimate	s.e.	parameter
6	-0.05300	0.02036	PKG(1).SCOR
7	0.1195	0.03098	PKG(2).SCOR
8	0.08691	0.02020	PKG(3).SCOR
9	0.1251	0.02515	PKG(1).AGE
10	0.5387	0.08904	PKG(2).AGE
11	0.003635	0.02004	PKG(3).AGE
12	-0.01920	0.4140	PKG(1).GRP(2)
13	-21.00	3.137	PKG(2).GRP(1)
14	-23.77	3.556	PKG(2).GRP(2)
15	-9.893	1.911	PKG(3).GRP(1)
16	-9.562	1.880	PKG(3).GRP(2)

correlation = 0.9449

F(14,14) = 17.14

tabulated value at 0.1% F(14,14) = 6.0

Table 40 - Dependent variable: tools ease of use (euse)

	estimate	s.e.	parameter
1	7.383	3.632	CONSTANT
2	-0.8359	0.3902	GRP(2)
3	-0.09402	0.03093	SCOR
4	-0.4315	0.4456	ELOC.PKG(1)
5	0.1782	0.2828	ELOC.PKG(2)
6	1.712	0.4806	ELOC.PKG(3)
7	0.1293	0.04690	PKG(1).TUT
8	-0.1768	0.06707	PKG(2).TUT
9	-0.003408	0.1010	PKG(3).TUT
10	-0.2921	0.3442	PKG(1).S
11	-0.3262	0.1867	PKG(2).S
12	0.3755	0.2510	PKG(3).S
13	-4.990	1.434	PKG(1).TECH(2)
14	8.811	3.532	PKG(2).TECH(1)
15	10.17	4.140	PKG(2).TECH(2)
16	-2.520	5.032	PKG(3).TECH(1)
17	-1.658	3.648	PKG(3).TECH(2)
18	2.175	1.081	PKG(1).CPKG(2)
19	-1.925	1.217	PKG(2).CPKG(2)
20	-1.818	1.199	PKG(3).CPKG(2)

correlation = 0.8466

F(10,10) = 5.521

tabulated value at 1% F(10,10) = 4.849

Table 41 - Dependent variable: time to think about how to execute primitive object (q1)

	estimate	s.e.	parameter
1	-56.17	95.86	CONSTANT
2	-120.5	32.24	HAND(2)
3	255.5	132.1	TECH(1).PKG(2)
4	305.6	136.8	TECH(1).PKG(3)
5	142.8	28.57	TECH(2).PKG(1)
6	167.5	148.6	TECH(2).PKG(2)
7	284.5	140.6	TECH(2).PKG(3)
8	-25.47	5.464	PKG(1).COMP
9	73.13	27.25	PKG(2).COMP
10	-6.044	5.308	PKG(3).COMP
11	3.737	1.009	PKG(1).SCOR
12	-8.250	2.781	PKG(2).SCOR
13	-2.115	1.230	PKG(3).SCOR
14	4.248	9.666	PKG(1).F
15	71.94	37.42	PKG(2).F
16	-1.816	5.622	PKG(3).F
17	-16.37	9.936	PKG(1).V
18	-43.34	21.46	PKG(2).V
19	24.34	7.248	PKG(3).V

correlation = 0.9051

F(11,11) = 9.538

tabulated value at 0.1% F(11,11) = 7.7

Table 42 - Dependent variable: time to think about how to execute cut object (q2)

	estimate	s.e.	parameter
1	-147.0	128.9	CONSTANT
2	50.19	31.53	GRP(2)
3	-32.09	8.951	COMP
4	110.3	55.48	PKG(1).TECH(2)
5	420.7	219.9	PKG(2).TECH(1)
6	262.0	223.1	PKG(2).TECH(2)
7	345.4	232.9	PKG(3).TECH(1)
8	332.1	262.4	PKG(3).TECH(2)
9	6.080	2.034	PKG(1).SCOR
10	-1.557	2.458	PKG(2).SCOR
11	0.3471	3.150	PKG(3).SCOR
12	-0.9185	0.6269	PKG(1).Q1
13	2.381	0.4238	PKG(2).Q1
14	-1.131	0.3479	PKG(3).Q1
15	-7.933	11.31	PKG(1).S
16	-25.77	8.616	PKG(2).S
17	52.52	12.78	PKG(3).S
18	68.33	43.36	PKG(1).CPKG(2)
19	-85.14	35.93	PKG(2).CPKG(2)
20	-73.29	70.99	PKG(3).CPKG(2)

correlation = 0.9019 from 28 observations

F(8,8) = 9.198

tabulated value at 0.5% F(8,8) = 7.496

Table 43 - Dependent variable: time to think about how to execute abstract object (q3)

	estimate	s.e.	parameter
1	-37.68	45.31	CONSTANT
2	-3.861	1.611	AGE
3	3.444	0.6889	SCOR
4	-41.04	28.30	SEX(1).PKG(2)
5	-85.04	42.23	SEX(1).PKG(3)
6	40.31	17.89	SEX(2).PKG(1)
7	-83.84	29.24	SEX(2).PKG(2)
8	6.984	36.61	SEX(2).PKG(3)
9	-7.900	38.73	PKG(1).CPKG(2)
10	5.529	17.14	PKG(2).CPKG(2)
11	-98.20	28.81	PKG(3).CPKG(2)
12	-0.2461	0.2357	PKG(1).Q1
13	0.3508	0.1523	PKG(2).Q1
14	0.2028	0.2598	PKG(3).Q1

correlation = 0.8404 from 29 observations

F(15,15) = 5.266

tabulated value at 0.5% F(15,15) = 4.0

Table 44 - Dependent variable: time to think about how to execute revolution object (q4)

	estimate	s.e.	parameter
1	72.66	30.47	CONSTANT
2	28.11	7.618	SEX(2)
3	-0.5366	0.5961	SCOR.PKG(1)
4	-6.246	0.6957	SCOR.PKG(2)
5	-2.749	0.5860	SCOR.PKG(3)
6	0.1162	0.1495	PKG(1).Q3
7	1.447	0.1653	PKG(2).Q3
8	0.1305	0.04437	PKG(3).Q3
9	-33.50	11.05	PKG(1).TECH(2)
10	229.0	50.34	PKG(2).TECH(1)
11	137.9	47.49	PKG(2).TECH(2)
12	189.6	57.34	PKG(3).TECH(1)
13	147.3	57.77	PKG(3).TECH(2)
14	-0.3711	3.216	PKG(1).F
15	24.54	3.762	PKG(2).F
16	-2.812	2.156	PKG(3).F
17	-0.09042	0.03795	PKG(1).Q2
18	0.1813	0.05309	PKG(2).Q2
19	-0.2392	0.08350	PKG(3).Q2

correlation = 0.9577

F(11,11) = 22.63

tabulated value at 0.1% F(11,11) = 7.7

Table 45 - Dependent variable: time to think about how to execute composite object (q5)

	estimate	s.e.	parameter
1	-12.06	17.50	CONSTANT
2	-4.189	1.606	S
3	0.1812	0.05078	Q3
4	0.03753	0.03886	Q2.PKG(1)
5	0.4301	0.06615	Q2.PKG(2)
6	-0.02377	0.07486	Q2.PKG(3)
7	21.28	8.860	PKG(1).GRP(2)
8	67.83	21.45	PKG(2).GRP(1)
9	56.51	19.60	PKG(2).GRP(2)
10	71.84	20.28	PKG(3).GRP(1)
11	95.42	22.22	PKG(3).GRP(2)

	estimate	s.e.	parameter
12	1.533	0.3405	PKG(1).Q4
13	-0.05421	0.1580	PKG(2).Q4
14	-0.1215	0.1776	PKG(3).Q4

correlation = 0.9040

F(16,16) = 9.414

tabulated value at 0.1% F(16,16) = 5.2

Table 46 - Dependent variable: time to think about how to execute general object (q6)

	estimate	s.e.	parameter
1	-504.4	118.3	CONSTANT
2	19.29	7.492	COMP
3	62.67	26.82	GRP(2)
4	0.6702	0.3755	Q4
5	1371.	219.1	SEX(1).PKG(2)
6	-25.52	225.7	SEX(1).PKG(3)
7	-55.46	36.59	SEX(2).PKG(1)
8	1359.	222.5	SEX(2).PKG(2)
9	-16.91	231.1	SEX(2).PKG(3)
10	6.882	2.410	PKG(1).SCOR
11	-12.76	2.577	PKG(2).SCOR
12	6.530	2.663	PKG(3).SCOR
13	0.7455	1.134	PKG(1).Q1
14	-1.395	0.3738	PKG(2).Q1
15	-0.3279	0.3817	PKG(3).Q1

correlation = 0.8515 from 28 observations

F(13,13) = 5.735

tabulated value at 0.5% F(13,13) = 4.5

Table 47 - Dependent variable: time to execute primitive object (t1)

	estimate	s.e.	parameter
1	-111.5	163.9	CONSTANT
2	208.8	69.17	TECH(2)
3	-256.3	86.64	MOUS(2)
4	6.171	0.9147	Q1.PKG(1)
5	0.8070	0.7136	Q1.PKG(2)
6	2.375	0.6650	Q1.PKG(3)
7	451.1	101.7	PKG(1).GRP(2)
8	1855.	538.4	PKG(2).GRP(1)
9	2215.	601.3	PKG(2).GRP(2)
10	-222.9	198.0	PKG(3).GRP(1)

	estimate	s.e.	parameter
11	-206.2	209.5	PKG(3).GRP(2)
12	-1.748	5.778	PKG(1).AGE
13	-83.37	27.29	PKG(2).AGE
14	15.61	4.892	PKG(3).AGE
15	-240.6	84.31	PKG(1).SEX(2)
16	-68.64	112.1	PKG(2).SEX(2)
17	-279.7	87.48	PKG(3).SEX(2)

correlation = 0.9119

F(13,13) = 10.35

tabulated value at 0.1% F(13,13) = 6.4

Table 48 - Dependent variable: time to execute cut object (t2)

	estimate	s.e.	parameter
1	851.7	385.4	CONSTANT
2	73.25	27.91	S
3	274.9	113.9	GRP(2)
4	-0.3862	0.9349	Q2.PKG(1)
5	5.472	1.144	Q2.PKG(2)
6	1.834	0.7236	Q2.PKG(3)
7	-55.56	14.91	PKG(1).AGE
8	29.42	58.09	PKG(2).AGE
9	-41.63	13.94	PKG(3).AGE
10	503.5	257.4	PKG(1).SEX(2)
11	-1775.	1210.	PKG(2).SEX(1)
12	-3011.	1488.	PKG(2).SEX(2)
13	800.5	554.7	PKG(3).SEX(1)
14	1258.	716.7	PKG(3).SEX(2)
15	129.3	56.47	PKG(1).F
16	240.1	72.20	PKG(2).F
17	-96.68	48.34	PKG(3).F
18	204.6	263.8	PKG(1).TECH(2)
19	373.5	239.3	PKG(2).TECH(2)
20	-851.1	317.3	PKG(3).TECH(2)

correlation = 0.9145

F(10,10) = 10.70

tabulated value at 0.1% F(10,10) = 8.754

Table 49 - Dependent variable: time to execute abstract object (t3)

	estimate	s.e.	parameter
1	2099.	579.4	CONSTANT
2	-73.37	23.39	V
3	4.645	2.129	Q3.PKG(1)
4	-12.16	3.414	Q3.PKG(2)
5	0.7299	0.4064	Q3.PKG(3)
6	477.1	191.2	PKG(1).TECH(2)
7	-6060.	1407.	PKG(2).TECH(1)
8	-4788.	1172.	PKG(2).TECH(2)
9	-3917.	1297.	PKG(3).TECH(1)
10	-3643.	1325.	PKG(3).TECH(2)
11	-0.1180	0.1732	PKG(1).T2
12	0.6668	0.2356	PKG(2).T2
13	0.8084	0.2586	PKG(3).T2
14	-22.91	9.827	PKG(1).SCOR
15	79.60	21.59	PKG(2).SCOR
16	28.94	12.88	PKG(3).SCOR
17	-5.464	150.7	PKG(1).SEX(2)
18	-633.9	264.8	PKG(2).SEX(2)
19	319.7	188.3	PKG(3).SEX(2)

correlation = 0.8983

F(11,11) = 8.836

tabulated value at 0.1% F(11,11) = 7.7

Table 50 - Dependent variable: time to execute revolution object (t4)

	estimate	s.e.	parameter
1	1051.	274.5	CONSTANT
2	-172.6	80.72	HAND(2)
3	-1.118	0.5746	Q4
4	-315.8	49.64	TECH(2)
5	0.4706	0.1094	T1
6	-7.358	3.073	SCOR.PKG(1)
7	-36.33	5.793	SCOR.PKG(2)
8	17.97	5.874	SCOR.PKG(3)
9	33.85	62.64	PKG(1).GRP(2)
10	1007.	409.8	PKG(2).GRP(1)
11	1417.	451.2	PKG(2).GRP(2)
12	-3027.	688.7	PKG(3).GRP(1)
13	-2984.	712.0	PKG(3).GRP(2)
14	-41.89	18.60	PKG(1).F
15	-16.98	22.20	PKG(2).F
16	24.91	16.42	PKG(3).F

	estimate	s.e.	parameter
17	-14.81	24.32	PKG(1).S
18	43.06	13.47	PKG(2).S
19	123.4	26.96	PKG(3).S
20	-0.2542	0.1379	PKG(1).T3
21	0.5368	0.1440	PKG(2).T3
22	0.6299	0.1592	PKG(3).T3

correlation = 0.9239

F(8,8) = 12.14

tabulated value at 0.1% F(8,8) = 12.05

Table 51 - Dependent variable: time to execute composite object (t5)

	estimate	s.e.	parameter
1	-48.42	306.0	CONSTANT
2	-288.7	65.11	TECH(2)
3	172.3	65.19	GRP(2)
4	15.69	4.978	AGE
5	0.3179	0.08041	T2
6	72.67	23.58	COMP.PKG(1)
7	-105.0	22.33	COMP.PKG(2)
8	-12.50	33.21	COMP.PKG(3)
9	-3.443	3.944	PKG(1).SCOR
10	15.19	4.099	PKG(2).SCOR
11	0.3484	3.945	PKG(3).SCOR
12	77.44	33.36	PKG(1).S
13	-7.318	22.36	PKG(2).S
14	116.8	39.89	PKG(3).S

correlation = 0.9108

F(16,16) = 10.21

tabulated value at 0.1% F(16,16) = 5.2

Table 52 - Dependent variable: time to execute general object (t6)

	estimate	s.e.	parameter
1	-511.6	381.1	CONSTANT
2	76.13	20.73	F
3	-119.3	577.8	TECH(1).PKG(2)
4	1769.	518.8	TECH(1).PKG(3)
5	-946.9	185.7	TECH(2).PKG(1)
6	436.5	577.6	TECH(2).PKG(2)
7	1671.	543.6	TECH(2).PKG(3)
8	1.542	0.3872	PKG(1).Q6
9	2.253	0.5593	PKG(2).Q6
10	-0.7021	0.3712	PKG(3).Q6
11	0.7560	0.3164	PKG(1).T3
12	-0.8593	0.1976	PKG(2).T3
13	0.005772	0.2629	PKG(3).T3
14	132.3	32.23	PKG(1).V
15	-150.7	29.43	PKG(2).V
16	88.29	36.78	PKG(3).V
17	0.6756	7.472	PKG(1).AGE
18	76.38	22.23	PKG(2).AGE
19	-31.96	7.800	PKG(3).AGE

correlation = 0.9303

F(11,11) = 13.34

tabulated value at 0.1% F(11,11) = 7.7

Appendix IX Linear Regression Analysis of Methods

For an introduction on linear regression analysis please refer to Section 6.2 on page 95.

INDEX TO INDEPENDENT VARIABLES:

AGE: subject's age

CPKG: previous CAD experience

COMP: previous computer experience

F: number of kinaesthetic answers in the VAK questionnaire

GRP(1): arts subjects

GRP(2): sciences subjects

HAND(1): right-handed

HAND(2): left-handed

MOUS(1): subject didn't have any problem with mouse

MOUS(2): subject had problem with mouse

PKG(1): Interactive Deformable Modeller (IDM), built by author, with forces

PKG(2): Interactive Modeller (IM), built by author, without forces

Q1: time to think about how to execute primitive object

Q2: time to think about how to execute cut object

Q3: time to think about how to execute abstract object

Q4: time to think about how to execute revolution object

Q5: time to think about how to execute composite object

Q6: time to think about how to execute general object

S: number of auditory answers in the VAK questionnaire

SATI: level of satisfaction with package

SATW: level of satisfaction with overall work

SCOR: spatial ability score

SEX(1): female

SEX(2): male

T1: time to execute primitive object

T1SA: level of satisfaction with resulting primitive object

T2: time to execute cut object

T2EN(1): subject finished building cut object

T2EN(2): subject gave up building cut object

T2EN(3): time was up for building cut object

T2SA: level of satisfaction with resulting cut object

T3: time to execute abstract object

T3SA: level of satisfaction with resulting abstract object

T4: time to execute revolution object

T5: time to execute composite object

T6: time to execute general object

T6RI(1): subject didn't produced right general object

T6RI(2): subject would have produced right general object if time wasn't up

T6RI(3): subject produced right general object

TECH(1): with no previous technical drawing experience

TECH(2): with previous technical drawing experience

TUT: time spent going through tutorial

V: number of visual answers in the VAK questionnaire

The column labelled "estimate" represents the regression coefficients whereas "parameter" gives the independent variable.

Regression analysis assumes constant variance and statistical independence between the cases. Standard residual plots of residual error against fitted values do not contradict these assumptions.

Table 53 - Regression of satisfaction with resulting abstract object (t3sa)

	estimate	s.e.	parameter
1	3.167	0.5852	1
2	2.533	0.7403	PKG(2)
3	1.833	0.9253	HAND(2)

correlation = 0.4099

Table 54 - Regression of satisfaction with resulting revolution object (t4sa)

	estimate	s.e.	parameter
1	5.048	0.4213	1
2	1.824	0.4026	PKG(2)
3	1.771	0.5000	HAND(2)
4	-0.003706	0.001450	T4

correlation = 0.6659

Table 55 - Regression of satisfaction with resulting composite object (t5sa)

	estimate	s.e.	parameter
1	5.610	0.6779	1
2	1.275	0.5803	PKG(2)
3	-0.002410	0.0008258	T5

correlation = 0.3837

Table 56 - Regression of satisfaction with all tasks combined (sa)

	estimate	s.e.	parameter
1	4.111	0.3086	1
2	1.256	0.3903	PKG(2)
3	1.431	0.4879	HAND(2)

correlation = 0.4273

Table 57 - Regression of satisfaction with resulting cut object (t2sa)

	estimate	s.e.	parameter
1	6.010	0.5967	1
2	-0.1258	0.7004	PKG(2)
3	-0.002154	0.0009372	T2

correlation = 0.2551

Table 58 - Regression of execution time for all the tasks combined (t)

	estimate	s.e.	parameter
1	458.6	79.42	1
2	-4.219	44.87	PKG(2)
3	2.917	0.8076	Q
4	-40.29	12.63	COMP

correlation = 0.5390

Table 59 - Dependent variable: level of satisfaction with package (sati)

	estimate	s.e.	parameter
1	-4.790	1.084	CONSTANT
2	0.2504	0.06536	S
3	0.3860	0.1466	SATW
4	-2.157	0.4653	PKG(1).TECH(2)
5	12.97	1.840	PKG(2).TECH(1)
6	11.13	1.713	PKG(2).TECH(2)
7	0.2206	0.03917	PKG(1).AGE
8	-0.08011	0.06709	PKG(2).AGE
9	0.8388	0.1777	PKG(1).T3SA
10	-0.5021	0.2333	PKG(2).T3SA

correlation = 0.9338

F(10,10) = 14.12

tabulated value at 0.1% F(10,10) = 8.754

Table 60 - Dependent variable: level of satisfaction with overall work (satw)

	estimate	s.e.	parameter
1	-1.455	0.8429	CONSTANT
2	0.08801	0.02827	AGE
3	0.2213	0.09270	T3SA.PKG(1)
4	0.5202	0.07996	T3SA.PKG(2)
5	0.2289	0.07846	PKG(1).F
6	-0.2287	0.08459	PKG(2).F
7	0.1950	0.08837	PKG(1).T5SA

	estimate	s.e.	parameter
8	0.4490	0.08291	PKG(2).T5SA
9	0.4361	0.1138	PKG(1).T2SA
10	0.1024	0.05974	PKG(2).T2SA

correlation = 0.9334

F(10,10) = 14.01

tabulated value at 0.1% F(10,10) = 8.754

Table 61 - Dependent variable: level of satisfaction with resulting primitive object (t1sa)

	estimate	s.e.	parameter
1	11.66	2.557	CONSTANT
2	0.3053	0.1448	COMP
3	-0.8525	0.5863	MOUS(2)
4	-0.2590	0.07546	AGE
5	7.477	3.449	TECH(1).PKG(2)
6	-0.5583	0.6570	TECH(2).PKG(1)
7	3.972	3.186	TECH(2).PKG(2)
8	-0.5113	0.6425	PKG(1).SEX(2)
9	2.995	0.8904	PKG(2).SEX(2)
10	0.005325	0.03399	PKG(1).SCOR
11	-0.1387	0.04857	PKG(2).SCOR
12	-0.4202	0.2496	PKG(1).V
13	-0.2314	0.1893	PKG(2).V

correlation = 0.8651

F(7,7) = 6.413

tabulated value at 2.5% F(7,7) = 4.995

Table 62 - Dependent variable: level of satisfaction with resulting cut object (t2sa)

	estimate	s.e.	parameter
1	1.762	0.9198	CONSTANT
2	-4.274	0.6789	T2EN(2)
3	-4.903	0.7110	T2EN(3)
4	0.4808	0.1243	T1SA
5	0.2876	0.07957	COMP
6	-0.8105	0.4086	GRP(1).PKG(2)
7	-1.365	0.4494	GRP(2).PKG(1)
8	-0.2375	0.4385	GRP(2).PKG(2)

correlation = 0.9169

F(12,12) = 11.04

tabulated value at 0.1% F(12,12) = 7.005

Table 63 - Dependent variable: level of satisfaction with resulting abstract object (t3sa)

	estimate	s.e.	parameter
1	-0.01574	0.6984	CONSTANT
2	0.8270	0.4420	HAND(2)
3	0.4679	0.1252	T1SA
4	-1.150	0.5106	CPKG(2)
5	3.458	0.4208	TECH(1).PKG(2)
6	2.295	0.4132	TECH(2).PKG(1)
7	2.776	0.5763	TECH(2).PKG(2)

correlation = 0.9132

F(13,13) = 10.52

tabulated value at 0.1% F(13,13) = 6.4

Table 64 - Dependent variable: level of satisfaction with resulting revolution object (t4sa)

	estimate	s.e.	parameter
1	3.844	1.295	CONSTANT
2	1.389	0.4356	HAND(2)
3	0.1551	0.09304	V
4	0.2061	0.09128	F
5	6.210	2.318	TECH(1).PKG(2)
6	1.277	0.4108	TECH(2).PKG(1)
7	5.311	2.318	TECH(2).PKG(2)
8	-0.04701	0.05086	PKG(1).AGE
9	-0.2211	0.09287	PKG(2).AGE

correlation = 0.8572

F(11,11) = 6.003

tabulated value at 0.5% F(11,11) = 5.3

Table 65 - Dependent variable: level of satisfaction with resulting composite object (t5sa)

	estimate	s.e.	parameter
1	-4.818	1.635	CONSTANT
2	-0.3311	0.1019	S
3	-2.023	0.5054	GRP(2)
4	-0.6588	0.3632	TECH(2)
5	0.1512	0.02502	SCOR.PKG(1)
6	-0.1257	0.03587	SCOR.PKG(2)
7	0.5694	0.1668	PKG(1).V
8	0.1485	0.1357	PKG(2).V
9	-0.9628	0.4887	PKG(1).SEX(2)
10	18.81	2.449	PKG(2).SEX(1)
11	20.33	2.602	PKG(2).SEX(2)

correlation = 0.9148

F(9,9) = 10.73

tabulated value at 0.1% F(9,9) = 10.0

Table 66 - Dependent variable: level of satisfaction with resulting general object (t6sa)

	estimate	s.e.	parameter
1	0.6780	2.574	CONSTANT
2	0.8301	0.2040	T5SA
3	0.6690	0.1788	T1SA
4	-24.72	4.476	T6RI(1).PKG(2)
5	1.673	1.136	T6RI(2).PKG(1)
6	-27.55	4.006	T6RI(2).PKG(2)
7	0.6775	0.7956	T6RI(3).PKG(1)
8	-26.03	4.129	T6RI(3).PKG(2)
9	-0.06347	0.03266	PKG(1).SCOR
10	0.3369	0.04524	PKG(2).SCOR

correlation = 0.9162

F(10,10) = 10.93

tabulated value at 0.1% F(10,10) = 8.754

Table 67 - Dependent variable: easy to locate tools (eloc)

	estimate	s.e.	parameter
1	-5.193	1.645	CONSTANT
2	0.3149	0.06354	AGE
3	-3.147	2.547	GRP(1).PKG(2)
4	1.804	0.4506	GRP(2).PKG(1)
5	-4.806	2.892	GRP(2).PKG(2)
6	-0.007192	0.01938	PKG(1).SCOR
7	0.08556	0.03527	PKG(2).SCOR
8	0.09182	0.1148	PKG(1).COMP
9	-0.2035	0.09327	PKG(2).COMP

correlation = 0.8472

F(10,10) = 5.545

tabulated value at 1% F(10,10) = 4.849

Table 68 - Dependent variable: tools ease of use (euse)

	estimate	s.e.	parameter
1	3.610	1.261	CONSTANT
2	-0.7102	0.4069	MOUS(2)
3	0.1309	0.04513	AGE
4	-0.1903	0.09029	S
5	1.465	0.4207	HAND(2)
6	-0.05646	0.01961	TUT
7	-0.5430	0.4583	SEX(1).PKG(2)
8	-1.789	0.4118	SEX(2).PKG(1)
9	-0.003558	0.4947	SEX(2).PKG(2)
10	0.5976	0.5146	PKG(1).GRP(2)
11	-1.338	0.4489	PKG(2).GRP(2)

correlation = 0.8781

F(9,9) = 7.207

tabulate value at 0.5% F(9,9) = 6.5

Table 69 - Dependent variable: time to think about how to execute primitive object (q1)

	estimate	s.e.	parameter
1	268.7	58.00	CONSTANT
2	-6.144	4.850	COMP.PKG(1)
3	11.89	5.683	COMP.PKG(2)
4	-3.148	0.8913	PKG(1).SCOR
5	-1.826	1.482	PKG(2).SCOR
6	9.945	19.00	PKG(1).SEX(2)
7	-88.20	106.5	PKG(2).SEX(1)
8	29.80	109.7	PKG(2).SEX(2)
9	47.52	18.79	PKG(1).GRP(2)
10	-76.95	25.16	PKG(2).GRP(2)
11	3.538	4.650	PKG(1).F
12	-23.76	9.580	PKG(2).F

correlation = 0.9115

F(8,8) = 10.30

tabulated value at 0.5% F(8,8) = 7.496

Table 70 - Dependent variable: time to think about how to execute cut object (q2)

	estimate	s.e.	parameter
1	428.8	103.6	CONSTANT
2	-15.54	5.405	S
3	-4.266	1.159	SCOR
4	-101.5	44.57	TECH(1).PKG(2)
5	24.01	23.70	TECH(2).PKG(1)
6	-293.9	61.62	TECH(2).PKG(2)
7	18.99	25.86	PKG(1).SEX(2)
8	81.08	29.10	PKG(2).SEX(2)
9	-0.5127	0.4473	PKG(1).Q1
10	1.072	0.2457	PKG(2).Q1

correlation = 0.8336

F(10,10) = 5.010

tabulated value at 1% F(10,10) = 4.849

Table 71 - Dependent variable: time to think about how to execute abstract object (q3)

	estimate	s.e.	parameter
1	-82.01	49.43	CONSTANT
2	226.8	90.59	TECH(1).PKG(2)
3	35.79	18.63	TECH(2).PKG(1)
4	226.7	92.79	TECH(2).PKG(2)
5	-0.7863	7.283	PKG(1).COMP
6	13.93	4.022	PKG(2).COMP
7	10.37	6.606	PKG(1).V
8	-11.33	4.913	PKG(2).V
9	0.5816	0.2311	PKG(1).Q2
10	-0.04919	0.1154	PKG(2).Q2
11	2.731	2.099	PKG(1).AGE
12	-5.155	3.986	PKG(2).AGE

correlation = 0.8281

F(8,8) = 4.816

tabulated value at 2.5% F(8,8) = 4.433

Table 72 - Dependent variable: time to think about how to execute revolution object (q4)

	estimate	s.e.	parameter
1	169.7	40.67	CONSTANT
2	0.6775	0.1094	Q2
3	-33.64	7.649	V
4	-605.1	153.4	SEX(1).PKG(2)
5	101.6	14.83	SEX(2).PKG(1)

	estimate	s.e.	parameter
6	-792.6	186.9	SEX(2).PKG(2)
7	4.003	5.834	PKG(1).F
8	81.33	16.81	PKG(2).F
9	-10.54	4.585	PKG(1).COMP
10	34.68	8.833	PKG(2).COMP
11	-4.155	1.711	PKG(1).AGE
12	12.54	4.689	PKG(2).AGE
13	62.03	17.74	PKG(1).GRP(2)
14	0.4076	14.80	PKG(2).GRP(2)

correlation = 0.9554

F(6,6) = 21.40

tabulated value at 0.1% F(6,6) = 20.03

Table 73 - Dependent variable: time to think about how to execute composite object (q5)

	estimate	s.e.	parameter
1	36.08	12.36	CONSTANT
2	-5.387	2.304	S
3	51.40	11.38	HAND(2)
4	0.3933	0.06509	Q2
5	31.29	10.62	TECH(1).PKG(2)
6	48.13	11.32	TECH(2).PKG(1)
7	28.94	13.00	TECH(2).PKG(2)

correlation = 0.8878

F(13,13) = 7.911

tabulated value at 0.1% F(13,13) = 6.4

Table 74 - Dependent variable: time to think about how to execute general object (q6)

	estimate	s.e.	parameter
1	41.97	59.97	CONSTANT
2	0.4780	0.1071	Q4
3	5.996	3.158	V
4	-440.0	122.0	GRP(1).PKG(2)
5	56.80	18.07	GRP(2).PKG(1)
6	-514.8	134.5	GRP(2).PKG(2)
7	6.631	8.394	PKG(1).S
8	-12.81	3.255	PKG(2).S
9	-0.6504	0.6569	PKG(1).SCOR
10	6.475	1.597	PKG(2).SCOR
11	-6.088	5.443	PKG(1).COMP
12	9.128	3.774	PKG(2).COMP

correlation = 0.9209 from 18 observations

F(6,6) = 11.63

tabulated value at 0.5% F(6,6) = 11.07

Table 75 - Dependent variable: time to execute primitive object (t1)

	estimate	s.e.	parameter
1	-1285.	368.3	CONSTANT
2	25.19	4.753	SCOR
3	-110.0	210.9	GRP(1).PKG(2)
4	-680.6	100.4	GRP(2).PKG(1)
5	-194.8	194.1	GRP(2).PKG(2)
6	7.536	1.507	PKG(1).Q1
7	0.5992	0.7292	PKG(2).Q1
8	-85.80	34.96	PKG(1).S
9	6.149	22.66	PKG(2).S
10	-159.1	68.59	PKG(1).TECH(2)
11	320.4	129.7	PKG(2).TECH(2)
12	117.9	76.00	PKG(1).SEX(2)
13	-324.6	116.8	PKG(2).SEX(2)

correlation = 0.9042

F(7,7) = 9.438

tabulated value at 0.5% F(7,7) = 8.885

Table 76 - Dependent variable: time to execute cut object (t2)

	estimate	s.e.	parameter
1	496.1	312.8	CONSTANT
2	9.782	1.542	Q2
3	6585.	1653.	TECH(1).PKG(2)
4	-263.2	128.4	TECH(2).PKG(1)
5	7433.	1913.	TECH(2).PKG(2)
6	-26.95	13.53	PKG(1).AGE
7	-306.0	75.75	PKG(2).AGE
8	481.5	222.5	PKG(1).MOUS(2)
9	-1594.	421.1	PKG(2).MOUS(2)
10	-67.43	42.89	PKG(1).COMP
11	-227.7	51.18	PKG(2).COMP
12	-150.5	193.2	PKG(1).GRP(2)
13	1264.	453.0	PKG(2).GRP(2)

correlation = 0.9315

F(7,7) = 13.60

tabulated value at 0.5% F(7,7) = 8.885

Table 77 - Dependent variable: time to execute abstract object (t3)

	estimate	s.e.	parameter
1	-517.6	214.3	CONSTANT
2	428.5	124.3	CPKG(2)
3	31.86	9.865	AGE
4	9.444	1.667	Q3.PKG(1)
5	4.640	1.564	Q3.PKG(2)
6	-19.98	25.19	PKG(1).F
7	254.0	45.82	PKG(2).F
8	-156.6	110.5	PKG(1).TECH(2)
9	-723.7	248.7	PKG(2).TECH(1)
10	-1064.	347.9	PKG(2).TECH(2)

correlation = 0.9090

F(10,10) = 9.985

tabulated value at 0.1% F(10,10) = 8.754

Table 78 - Dependent variable: time to execute revolution object (t4)

	estimate	s.e.	parameter
1	842.5	117.3	CONSTANT
2	0.8959	0.2964	Q4
3	-46.44	7.343	COMP
4	-9.737	2.064	SCOR
5	76.63	37.71	MOUS(1).PKG(2)
6	363.5	77.56	MOUS(2).PKG(1)
7	-134.9	49.85	MOUS(2).PKG(2)
8	-84.91	59.77	PKG(1).GRP(2)
9	306.8	51.34	PKG(2).GRP(2)

correlation = 0.8974

F(11,11) = 8.747

tabulated value at 0.1% F(11,11) = 7.7

Table 79 - Dependent variable: time to execute composite object (t5)

	estimate	s.e.	parameter
1	-696.5	312.6	CONSTANT
2	0.6627	0.1333	T3
3	1.719	0.3569	T4
4	2269.	630.6	TECH(1).PKG(2)
5	194.1	113.9	TECH(2).PKG(1)
6	1763.	663.5	TECH(2).PKG(2)
7	-233.5	104.1	PKG(1).GRP(2)
8	339.5	115.4	PKG(2).GRP(2)
9	30.27	13.84	PKG(1).AGE
10	-64.63	27.26	PKG(2).AGE

correlation = 0.9062

F(10,10) = 9.662

tabulated value at 0.1% F(10,10) = 8.754

Table 80 - Dependent variable: time to execute general object (t6)

	estimate	s.e.	parameter
1	-1843.	340.7	CONSTANT
2	3.354	0.3277	T4
3	14.97	3.671	SCOR
4	2148.	548.9	TECH(1).PKG(2)
5	358.3	106.0	TECH(2).PKG(1)
6	2978.	579.4	TECH(2).PKG(2)
7	82.65	27.77	PKG(1).F
8	-138.2	34.54	PKG(2).F
9	24.21	11.69	PKG(1).AGE
10	-50.74	21.86	PKG(2).AGE

correlation = 0.9301

F(10,10) = 13.30

tabulated value at 0.1% F(10,10) = 8.754

Appendix X Interpretation of Linear Regression per Task

X.1 User interface analysis

For the correct interpretation of the results to be presented it is important to note that for each variable (for example age or score or sex and so on) the set of statements made below are held true only if one would look at each variable assuming that all the other ones are equal, i.e. there is no difference amongst subjects in an experiment apart from the variable being looked at.

Table 81 - Level of Satisfaction with application

Satisfaction with application	**IM**	**I3DM**	**Swivel3D**
Previous technical drawing experience	No	Yes	Yes
Number of auditory answers in VAK quest		-	+
Satisfied with resulting general object			+
Duration of whole experiment	-	-	+
Group (arts/sciences)	Arts	Sciences	Arts

Table 81 above shows the correlations found for the level of satisfaction with the applications and other things being equal should read: in IM previous technical drawing experience and a longer time to execute the whole experiment did not increase the level of satisfaction with the application. In addition Arts students rather than Sciences students were more satisfied and the same was observed for Swivel3D. In I3DM however the opposite occured, Sciences students were more satisfied than Arts students. Previous technical drawing experience beneffited I3DM and Swivel3D. In Swivel3D other positive associations with the level of satisfaction with the application were found. These related to a high auditory represenation system, a high level of satisfaction with the resulting general object and the longer duration of the whole experiment. In I3DM, other associations included a low auditory represenation system and a shorter duration for the experiment.

So following this convention the other 21 similar tables can be analyzed.

Table 82 - Level of Satisfaction with Overall Work

Satisfaction with Work	IM	I3DM	Swivel3D
Satisfied with resulting primitive object	+	+	+
Number of auditory answers in VAK quest	-	-	
Satisfied with resulting general object		-	+
Number of visual answers in VAK quest.		+	

Table 83 - Level of Satisfaction with Resulting Primitive Object

Satisfaction with Resulting Primitive Object	IM	I3DM	Swivel3D
Number of auditory answers in VAK quest	+	+	
Previous technical drawing experience	No		
Spatial ability score	-		+

Table 84 - Level of Satisfaction with Resulting Cut Object

Satisfaction with Resulting Cut Object	IM	I3DM	Swivel3D
Finish cut object	Yes	Yes	
Previous technical drawing experience	No	No	Yes
Computer experience	+	+	-

Table 85 - Level of Satisfaction with Resulting Abstract Object

Satisfaction with Resulting Abstract Object	IM	I3DM	Swivel3D
Satisfied with resulting primitive object	+	-	+
Previous technical drawing experience	Yes		No
Computer experience		+	

Table 86 - Level of Satisfaction with Resulting Revolution Object

Satisfaction with Resulting Revolution Obj	IM	I3DM	Swivel3D
Satisfied with resulting cut object		+	+
Group (arts/sciences)	Arts	Sciences	Sciences
Previous technical drawing experience		Yes	
Sex		Female	

Table 87 - Level of Satisfaction with Resulting Composite Object

Satisfaction with Resulting Composite Obj	IM	I3DM	Swivel3D
Group (arts/sciences)			Arts
Spatial ability score	-		+
Age	+	-	+

Table 88 - Level of Satisfaction with Resulting General Object

Satisfaction with Resulting General Object	IM	I3DM	Swivel3D
Produced right result	Maybe	No	
Satisfied with resulting revolution object	+		+
Previous technical drawing experience	No		Yes
Number of visual answers in VAK quest.	+		-

Table 89 - How Easy it is to Locate Tools

Locating Tools	IM	I3DM	Swivel3D
Number of auditory answers in VAK quest	+	+	
Spatial ability score	-	+	-
Age	-	-	
Group (arts/sciences)	Sciences		Arts

Table 90 - How Easy it is to Use Tools

Using Tools	IM	I3DM	Swivel3D
How easy it was to locate tools			-
Time spent in tutorial	+	-	
Num. of kinaesthetic answers in VAK qst	+		-
Previous technical drawing experience	No	Yes	
Previous CAD experience	Yes	No	Yes

Table 91 - Time to Think about Primitive Object

Time Thinking about Primitive Object	IM	I3DM	Swivel3D
Previous technical drawing experience	Yes	No	Yes
Computer experience	-	+	
Spatial ability score	+	-	+
Num. of kinaesthetic answers in VAK qst	-		
Number of visual answers in VAK quest.	+	+	-

Table 92 - Time to Think about Cut Object

Time Thinking about Cut Object	IM	I3DM	Swivel3D
Previous technical drawing experience	Yes	No	Yes
Spatial ability score		-	
Time spent thinking about primitive object	-	+	+
Number of auditory answers in VAK quest	+		-
Previous CAD experience	Yes	No	

Table 93 - Time to Think about Abstract Object

Time Thinking about Abstract Object	IM	I3DM	Swivel3D
Sex	Male	Female	Female
Previous CAD experience			Yes
Time spent thinking about primitive object	-		

Table 94 - Time to Think about Revolution Object

Time Thinking about Revolution Object	IM	I3DM	Swivel3D
Spatial ability score	+		+
Time spent thinking about abstract object	-		-
Previous technical drawing experience	Yes	Yes	Yes
Num. of kinaesthetic answers in VAK qst	-		
Time spent thinking about cut object	-	+	+

Table 95 - Time to Think about Composite Object

Time Thinking about Composite Object	IM	I3DM	Swivel3D
Time spent thinking about cut object	-		
Group (arts/sciences)	Sciences	Arts	Arts
Time spent thinking about revolution obj.		-	

Table 96 - Time to Think about General Object

Time Thinking about General Object	IM	I3DM	Swivel3D
Sex	Male	Male	
Spatial ability score	+	-	-
Time spent thinking about primitive object	+		

Table 97 - Time to Execute Primitive Object

Time Executing Primitive Object	IM	I3DM	Swivel3D
Time spent thinking		-	-
Group (arts/sciences)	Arts	Arts	
Age	+		-
Sex		Male	Male

Table 98 - Time to Execute Cut Object

Time Executing Cut Object	IM	I3DM	Swivel3D
Time spent thinking	-		-
Age		+	+
Sex	Male	Female	Female
Num. of kinaesthetic answers in VAK qst	-	-	+
Previous technical drawing experience	No		Yes

Table 99 - Time to Execute Abstract Object

Time Executing Abstract Object	IM	I3DM	Swivel3D
Time spent thinking	+	-	-
Previous technical drawing experience	No	No	No
Time spent on cut object	-		-
Spatial ability score	-	+	-
Sex	Male		Female

Table 100 - Time to Execute Revolution Object

Time Executing Revolution Object	IM	I3DM	Swivel3D
Spatial ability score	+	+	-
Group (arts/sciences)	Arts		Arts
Num. of kinaesthetic answers in VAK qst		+	-
Number of auditory answers in VAK quest	-		-
Time spent on abstract object	-	+	-

Table 101 - Time to Execute Composite Object

Time Executing Composite Object	IM	I3DM	Swivel3D
Computer experience	+	-	
Spatial ability score	-		
Number of auditory answers in VAK quest		-	-

Table 102 - Time to Execute General Object

Time Executing General Object	**IM**	**I3DM**	**Swivel3D**
Previous technical drawing experience		Yes	Yes
Time spent thinking	-	-	+
Time spent on abstract object	+	-	
Number of visual answers in VAK quest.	+	-	-
Age	-		+

Table 103 - Level of Satisfaction with application

Satisfaction with application	IDM	IM
Previous technical drawing experience	No	No
Age	+	
Satisfied with resulting abstract object	+	-

Table 104 - Level of Satisfaction with Overall Work

Satisfaction with Work	IDM	IM
Satisfied with resulting abstract object	+	+
Num. of kinaesthetic answers in VAK qst	+	-
Satisfied with resulting composite object	+	+
Satisfied with resulting cut object	+	+

Table 105 - Level of Satisfaction with Resulting Primitive Object

Satisfaction with Resulting Primitive Object	IDM	IM
Previous technical drawing experience		No
Sex		Male
Spatial ability score		-
Number of visual answers in VAK quest.	-	

Table 106 - Level of Satisfaction with Resulting Cut Object

Satisfaction with Resulting Cut Object	IDM	IM
Group (arts/sciences)	Arts	Sciences

Table 107 - Level of Satisfaction with Resulting Abstract Object

Satisfaction with Resulting Abstract Object	IDM	IM
Previous technical drawing experience	Yes	No

Table 108 - Level of Satisfaction with Resulting Revolution Object

Satisfaction with Resulting Revolution Obj	IDM	IM
Previous technical drawing experience	Yes	No
Age		-

Table 109 - Level of Satisfaction with Resulting Composite Object

Satisfaction with Resulting Composite Obj	IDM	IM
Spatial ability score	+	-
Number of visual answers in VAK quest.	+	
Sex	Male	Male

Table 110 - Level of Satisfaction with Resulting General Object

Satisfaction with Resulting General Object	IDM	IM
Produced right result	Maybe	No
Spatial ability score	-	+

Table 111 - How Easy it is to Locate Tools

Locating Tools	IDM	IM
Group (arts/Sciences)	Arts	Sciences
Spatial ability score		-
Computer Experience		+

Table 112 - How Easy it is to Use Tools

Using Tools	IDM	IM
Sex	Female	
Group (arts/sciences)		Sciences

Table 113 - Time to Think about Primitive Object

Time Thinking about Primitive Object	IDM	IM
Computer Experience	+	-
Group (arts/sciences)	Arts	Sciences
Sex		Female
Num. of kinaesthetic answers in VAK qst		+

Table 114 - Time to Think about Cut Object

Time Thinking about Cut Object	IDM	IM
Previous technical drawing experience		Yes
Sex		Female
Time thinking about primitive object		-

Table 115 - Time to Think about Abstract Object

Time Thinking about Abstract Object	IDM	IM
Previous technical drawing experience	No	Yes
Computer experience		-
Number of visual answers in VAK quest.	-	+
Time thinking about cut object	-	
Age	-	+

Table 116 - Time to Think about Revolution Object

Time Thinking about Revolution Object	IDM	IM
Sex	Female	Male
Num. of kinaesthetic answers in VAK qst		-
Computer experience	+	-
Age	+	-
Group (arts/sciences)	Arts	

Table 117 - Time to Think about Composite Object

Time Thinking about Composite Object	IDM	IM
Previous technical drawing experience	No	Yes

Table 118 - Time to Think about General Object

Time Thinking about General Object	IDM	IM
Group (arts/sciences)	Arts	Sciences
Number of auditory answers in VAK quest		+
Spatial ability score		-
Computer experience		-

Table 119 - Time to Execute Primitive Object

Time Executing Primitive Object	IDM	IM
Group (arts/sciences)	Sciences	
Time spent thinking	-	
Number of auditory answers in VAK quest	+	
Previous technical drawing experience	Yes	No
Sex	Female	Male

Table 120 - Time to Execute Cut Object

Time Executing Cut Object	IDM	IM
Previous technical drawing experience	Yes	No
Age	+	+
Problems with mouse	No	Yes
Computer experience	+	+
Group (arts/sciences)		Arts

Table 121 - Time to Execute Abstract Object

Time Executing Abstract Object	IDM	IM
Time spent thinking	-	-
Num. of kinaesthetic answers in VAK qst		-
Previous technical drawing experience	Yes	Yes

Table 122 - Time to Execute Revolution Object

Time Executing Revolution Object	IDM	IM
Problems with mouse	No	Yes
Group (arts/sciences)	Sciences	Arts

Table 123 - Time to Execute Composite Object

Time Executing Composite Object	IDM	IM
Previous technical drawing experience	No	Yes
Group (arts/sciences)	Sciences	Arts
Age	-	+

Table 124 - Time to Execute General Object

Time Executing General Object	IDM	IM
Previous technical drawing experience	No	No
Num. of kinaesthetic answers in VAK qst	-	+
Age	-	+