LANDMARK UNIVERSITY, OMU-ARAN

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COLLEGE: COLLEGE OF SCIENCE AND ENGINEERING
DEPARTMENT: MECHANICAL ENGINEERING
PROGRAMME: MCE 511
ENGR. ALIYU, S.J

Course title: Computer-Aided Engineering Design and Analysis
Course unit: 2 UNITS.
Course Content:

Overview of Computer-Aided Design and Analysis: History of CAD/E, characteristics of CAD/E, overview of the industrial application of CAD, CAE, and CAM, functions of CAD/CAE/CAm systems, information embedded in a CAD system, tools commonly used in CAD. Hardware and software of a CAD/E System; Computer hardware, typical CAD/CAE.CAM system configuration, concepts of graphics display, various input and output devices, data structure and database management systems, graphical coordinate systems, software function and application modules, current Geometric Transformation - 2-D and 3-D geometric transformation, projections, generation of multiple views for an engineering drawing Curve and Surface Modeling; Parametric representation, analytical and synthetic curves, Hermite cubic splines, Bezier curves, B-Spline curves, introduction of NURBS, surface patch, bilinear surface, lofted surface, bi-cubic surface, Bezier surface, B-spline surface, surface offset and blend Geometric Modeling; Comparison of wireframe, surface and solid modeling, CSG, B-rep solid modeling techniques, feature-based parametric modeling, CAD/CAM data exchange methods, IGES, STEP and PDES. Basics of Finite Element Analysis (FEA) - Concepts of elements and discretization, unit displace method, procedure of finite element analysis on computer; automatic mathematical problem formulation in computer, truss element, commonly used model and element types, limitations and common misconceptions about FEA

COMPUTER AIDED DESIGN AND ANALYSIS

1.0 INTRODUCTION

1.1 Computer Aide Design

Computer aided design is the integration of human and computer to achieve optimum design and manufacturing of a product. The application of computer in design allows designers to fashion and test their ideas interactively in real time without having to create real prototypes as in conventional strategies to design.

CAD creates virtual models (CAD prototypes) and displayed them on computer screen for the purpose of getting views into what reality might be and how to prepare for the product use.

CAD is required to enhance the level of productivity in creating or modification of designs.

1.2 Parametric design

It is a design technique in which geometric entities are use for creating the desire dimensions of components. The geometric entities include lines, arcs, circles and splines. These dimensions define parameters that control part geometry. Since parameters control geometry, the geometry is said to be dimension driven. Hence, only the geometric aspects are required to satisfy the design relationships.

Parameters can also be driven by dimensional values, or other parameters using formula that relates specific feature geometry to volume, stress, temperature etc used in parametric design.

In parametric design, when the parameters change, other parameters driven by the modification also change.

Parametric design is very popular in computer aided design for the following reasons:

• Separation of variables

• Each variable is treated alike

• More degrees of freedom/control

• Parametric equations can be transformed directly

• Infinite slopes can be handled without computational breakdown

• Easy to express as vectors

• Amenable to plotting and digitizing

• Inherently bounded

Advantages

1. It enables users to manipulate the length, angle and pitch of a particular component.
2. It also enables users to know the complex relationships that exist among parts of an assembly, e.g meshing of two gears.
3. Design produce from parametric design are more meaningful than those generated by traditional CAD systems.
4. Engineers can work with the same solid model, extract and add information according to need.

Disadvantages

1. It is limited to the set of geometric or engineering relationship provided by the engineers for creating the design components.
2. The limited set of geometric entities can make it difficult to change parametric design model once the initial conditions have been set.
3. The technique is suitable for design tasks that do not involve many variations in the design strategy.

1.3 Variational design

This design is essentially governed by a set of engineering equations relating its geometry and functions. In variational design, geometric entities and engineering equations with important relationships among the elements of design can be solved simultaneously.

When compare to parametric approach, variational system is able to determine the position of geometric elements and constraints. Besides, it is able to handle the coupling between parameters in the geometric constraints and engineering equations. Variational design concept helps the engineer evaluate the design of component in depth instead of considering only geometric aspects to satisfy the design relationship.

Variational design has the ability to incorporate optimization into the design environment. The engineer can then specify both equality and inequality design constraints. The objective function is a set of both dependent and independent variables that can be optimize relative to one or more independent variables.

1.4 Innovative process in product development

The focus and ultimate goal of an engineer is to be able to answer the following questions:

1. Do design (geometry) and choice of material allow intended product to achieve the performance required by technical specification?
2. What is the optimum achievable performance?
3. Will the design be sensitive to manufacturing tolerances?

Answering these questions require one to solve equations relating output and input conditions. The known quantities are the various targeted performance of products (e.g static or model behaviour), and the unknown of the problems are of several form: geometric dimensions, material characteristics, shell thickness, and density of weld spots.

1.5 Problems facing design engineers:

- Higher customer quality expectations.
- Need to have innovation and originality in design.
- Need for global collaboration across and beyond the enterprise among designers, customers and vendors to reduce development lead times.
- Need to evaluate feasibility throughout the design process.

- Ability to react quickly to design changes as and when change requests are made.
- Ability to express the design intent in terms of shape and function using the tools available as well as the ability of the tools to transfer data back and forth seamlessly.

1.6 CAD SYSTEMS DESIGN PROCESS

1.6.1 Geometric modeling

In geometric modeling, a physical object or any of its components is described mathematically. The designer first constructs a geometric model by giving commands through the CPU of the CAD system to create or modify lines, surfaces, solids, dimensions and text that are all together accurate and complete representation of 2D and 3D object.

The model can be represented in three different ways; line, surface and solid. In line (wire-frame) representation, all edges are visible as solid lines. This image can be confusing for complex shapes. However, various colours are generally used for different parts of the object to ensure proper visualization. In surface model, all visible surfaces are shown, and in solid model, all surfaces are shown but the data describe the interior volume.

1.6.2 Design review and evaluation

This is an important stage to check for any interference between various components in order to prevent difficulties during assembly or use of the part, and whether moving members, such as linkages, are going to operate as intended.

CAD systems contain kinematic packages which provide the capability to animate the motion of design component to identify potential problems associated with moving parts and other dynamic situations. Animation of object enables the designer to properly visualize the mechanism operation and guide against any interference with other components. During design review and evaluation stage, the part is precisely dimensioned and tolerance, as required for manufacturing.

1.6.3 Automated drafting

Automated drafting is concerned with the production of hard-copy engineering drawings directly from CAD system database for documentation and reference. Computer-aided design has some graphic features that are suitable for drafting process. These features include automatic dimensioning, generation of cross-hatched areas, scaling of the drawing, and the capacity to develop sectional views and enlarged views of particular part detailed. It also has the ability to rotate the part of to perform other transformation of the image.

The early use of computer in design has been justified by increase productivity in drafting function compared to manual drafting.

1.6.4 Engineering analysis

After the design geometric features have been determined, the design is subjected to an engineering analysis to evaluate its performance. The design performance characteristics include stress-strain, heat transfer and fluid flow.

1.7 DESIGN ANALYSIS METHODS

Design analysis can be achieved by two methods: analytical and experimental.

1.7.1 Analytical method

In this method, different types of analysis can be performed using packages available for computer aided design. These include finite element analysis, kinematic analysis and synthesis, and static and dynamics analysis.

1.7.2 Experimental method

In this method, testing is conducted on prototypes and models with the intension to obtain either material properties or validate performance characteristics of a particular design.

Testing in the conventional design is done to quantify the design after manufacturing. With computer aided design, testing is used throughout the development cycle and to make better use of test data via advanced analysis techniques, and to integrate these within other disciplines involved in design.

Initial testing can be done on a prototype or on different components to understand model response to certain loading conditions.

Experimental data are useful in the analysis of models where analytical solutions are not reliable. The data can also be used to refuse refine finite element models for large scale analysis. Hence the integration of experimental tests with analytical tools results in more effective engineering analysis.

Computer aided design provides the ultimate tool for combining such method with the graphics capabilities to allow the designer obtain realistic and effective design with a minimum span of time.

2.0 GEOMETRIC MODELING TECHNIQUES

2.1 Introduction

Geometric modeling is concern with the representation of a system or component geometry either with conventional drawing or computer software packages. The component or system geometries are called geometric models.

The techniques are wire frame modeling, surface modeling and solid modeling.

2.1.1 Wire frame modeling

In this type of modeling scheme, the object is represented by its edges. The wire frame model of an object appears as if it is made of wires as shown in figure 2.1. The models produces include 2D or 3D wire frame.

Wire frame models are simple and easy to create, and require relatively little computer time and memory. They do not provide complete description of the object. They also contain little information about the surface and volume of the part. Although wire frame modeling is ambiguous in understanding the object, this has been the method traditionally used in the 2D representation of the object, where orthographic views such as plane, elevation, end view, etc are employed to described the object graphically.

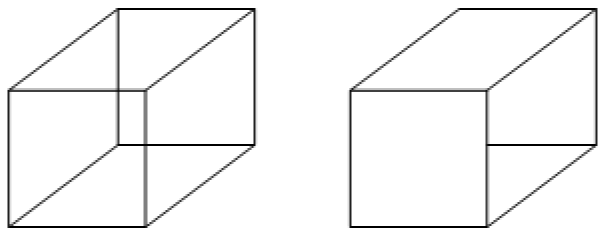

Figure 2.1: Wire frame models

Comparison between 2D and 3D wire frame models

2D models	3D wire frame models
1. End (vertices) of lines are represented by their X and Y coordinates.	End of lines are represented by their X, Y and Z coordinates.
2. Curved edges are represented by circles, ellipses, splines, etc.	Curves surfaces are represented by suitably spaced generators.
3. Additional views and sectional views are required to represent a complex object with clarity.	Hidden line or hidden surface elimination is a must to interpret complex components correctly.
4. 3D image reconstruction is tedious	2D views as well as various pictorial views can be generated easily.
5. It uses only one global coordinate system	It may require the use of several coordinate systems on different faces of the components.

2.1.2 Surface modeling

In geometric surface modeling, a component is represented by its surfaces which in turn are represented by their vertices and edges. For example, eight surfaces are combined together to create a component shown in figure 2.2.

Surface modeling systems are useful to calculate surfaces intersections and surface areas. The systems are capable of producing shaded images and removing hidden lines automatically.

Surface model can be constructed using a large variety of surface feature or standard surface convections (e.g box, pyramid, wedge, dome, sphere, cone, torus, dish and mesh) available in CAD systems.

More complex shapes can be defined surface of revolution, surface sculptured, sweep surface and fillet-surfaces.

Surface models do not represent the solid nature of parts because they contain no information describing what is within the part interior. They cannot be used as a basis in engineering analysis programmes such as finite element and modal analysis for stress and strain predictions. However, surface models are used where complex 3D geometries must be designed, especially where the application has to do with the exterior shell of objects such as sheet metal and thin moulded plastic parts.

Surface modeling has been popularly use in aerospace and automobile industries. Surface model require more computational time and memory compared to wire frame.

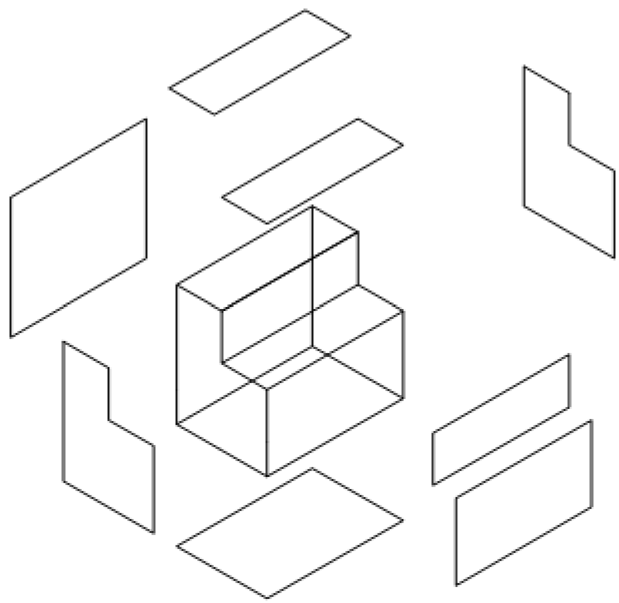

Figure 2.2: Surface representation

2.1.3 Solid modeling

Solid models are true 3D representation of physical object as shown in Figure 2.3. This is due to the fact that solid model is bounded, homogeneously three dimensional and finite. Solid modeling is an accurate geometric description which includes both the external surface and internal structure of the object. It allows the designer to determine information such as the object mass properties, interference, and internal cross sections.

Solid models differ from wire frame and surface models in the kind of geometric information they provide. Wire frame models only show the edge geometry of an object. They give no information about what is inside an object. Surface models provide surface information, but lack information about object internal structure. Solid models provide complete geometric descriptions of objects.

Solid models can be used in design analysis to yield reliable results. Solid models apart from geometric information also provide important data such as volume, mass, properties and centre of gravity.

The designer can also export models created to other applications for finite element analysis (FEA), rapid prototyping and other special engineering applications.

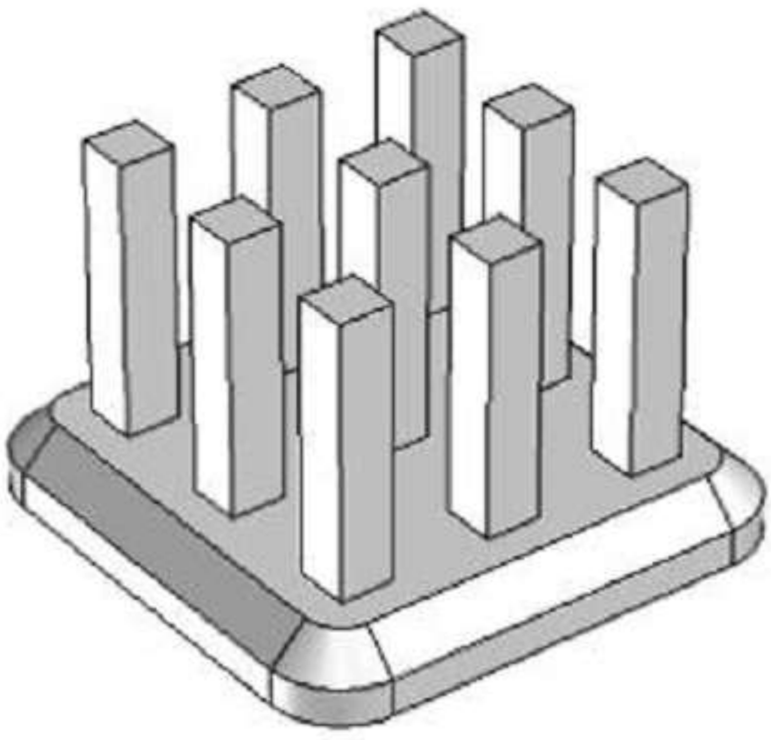

Figure 2.3: 3D model of heat sink

2.2 CONSTRUCTIVE SOLID GEOMETRY (CSG)

In a CSG model, physical objectives are created by combining basic elementary shapes known as primitives like block, cylinders, cones, pyramids and spheres. The Boolean operations such as union, difference and intersection are used to obtain the require geometry.

A “union” operation (AUB) will combine the two to convert them into a new solid. The difference operation (A - B) will create a block with a hole. An intersection operation (AnB) will yield the portion common to the two primitives.

2.3 Boundary Representation

Boundary representation is created based on the fact that a physical object is enclosed by a set of faces which themselves are closed and orientable surfaces. In this model, face in bound by edges and each is bounded by vertices.

3.0 CURVES AND SURFACE MODELING

Modeling of curves and surfaces is required to describe objects that are encountered in several areas of mechanical engineering design. Curves and surfaces are the basic building blocks in the following designs:

i. Body panels of passenger cars

ii. Aircraft bulk heads and other fuselage structures, slats, flaps, wings etc.

iii. Marine structures

iv. Consumer products like plastic containers, telephones etc.

v. Engineering products like mixed flow impellers, foundry patterns etc

3.1 CURVE REPRESENTATION

3.1.1 Parametric form

Mathematically, curve is a polynomial function whose first and second derivatives are continuous over any point of the curve. A point on a curve can be represented as a vector

$$P(u) = [x(u), y(u), z(u)]$$

where x, y, z are co-ordinates of the points on the curve which are functions of some parameter u and the parametric variable is constrained in the interval.

The parametric equations of some commonly used curves are:

(i). Straight line: equations of straight line in parametric form are:

$$x = x_0 + (x_1 - x_0)t$$

$$y = y_0 + (y_1 - y_2)t$$

$$z = z_0 + (z_1 - z_0)t$$

Where $0 \le t \le 1$

(ii). Circle: circle is a loci of a point moving in plane such that its distance from a fixed point called centre is constant. Its equation is given by

$$x = r\cos\theta$$

$$y = r\sin\theta$$

Where $0 \le \theta \le 360$

(iii). Ellipse: An ellipse is a loci of a point moving in space such that at any position, the sum of its distance from two fixed points called loci is constant and equal to the major diameter. The parametric equation can be represented as

$x = a\cos\phi$

$y = b\sin\phi$

3.1.2 Non-parametric form

The non-parametric curve representation is one in which any generic point (x, y, z) satisfies a relationship in implicit form in x, y, and z i.e. f(x, y, z) = 0. This can be expressed in an explicit form as:

$$x = g1(y, z)$$

$$y = g2(x, z)$$

$$z = g3(x, y)$$

3.2 DESIGN OF CURVED SHAPES

A component can be designed using the curves and shapes which can be mathematically described e.g. arc, circle, conics, ellipsoid, hyperbolic paraboloid, sphere, and cone, cylinder, linear, conical - and circular swept surfaces etc. However, very often the designer starts with specifying a few points which roughly describe the shape.

Two approaches are available to designers for modeling curves and surfaces: interpolation and approximation.

The interpolation essentially tries to pass a curve on a surface called interpolant through all the points. Approximation tries to fit a smoother curve on surface which may be close to these points but may not actually pass through each of them.

Design of curved shapes should satisfy the following requirements:

i. It should be possible to represent the shape mathematically.

ii. The modeling should involve minimum computation.

iii. It should be possible to generate a CNC program to machine the surfaces (2, 3, 4 and 5 axis machining) or to prepare a mould or die to make the part (as in plastic injection molding or casting or automobile panel pressing).

3.3 SPACE CURVES

Space curves are used to generate curve shapes without the prior knowledge of the curve shape. In this method of curve representation, only few point on the curve pass through the control points used to define a curve.

3.3.1 Spline curve

Splines are functions used for fitting a curve through a number of data points. They are used in computer graphics packages to design complex curves and surfaces such as designing automobile and aircraft bodies, hull of ship, etc.

Spline curve is a composite curve with polynomial sections. These sections must meet certain continuity conditions at the boundary of the sections. There should be a smooth transition from one section to the other. If each section of a spline is described with a set of parametric coordinate functions of form x = f(u), y = f(u), z = f(u), parametric continuity is set by matching the derivatives of adjoining curve sections at their common boundary.

3.3.2 Cubic splines

Cubic splines are used in drawings to specify paths for object motion. They are specified by cubic polynomial to ensure optimum flexibility and speed of computation. Cubic splines require less computation time and memory and are more stable compare to higher polynomial. When compare with lower polynomial, cubic splines are more flexible for modeling arbitrary curve shapes. For cubic splines, the set of equations in parametric form can be written as:

$$x(t) = a_x + b_x t + c_x t^2 + d_x t^3$$

$$y(t) = a_y + b_y t + c_y t^2 + d_y t^3$$

$$z(t) = a_z + b_z t + c_z t^2 + d_z t^3$$

Where $0 \le t \le 1$

3.3.3 B-spline curves

The B-spline curves are used to generate complex geometry curves with continuity at joints when curves are pieced together. The curve depends on the blending function to confine the effects of a control point movement to the immediate location.

The equation for this curve can be written as:

$$P(u) = \sum_{i=0}^{n} P_i N_i, j(u)$$

Where N_i, j is called the blending function.

The blending functions are defined recursively as:

$N_i = 1$ if t_i < u < $t_i + 1$ = 0 otherwise

$$N_i, j(u) = \frac{(u - t_i)N_i, j - 1(u)}{t_i + j - 1 - t_i} + \frac{(t_i + j - u)N_i + 1, j - 1(u)}{t_i + j - t_i + 1}$$

When the control points are distinct, this curve is continuous in slope and in curvature between successive segments but it does not pass through any of the intermediate control points. The cubic B-spline has the advantage that the control points may be moved without affecting slope and curvature continuity and only four spans of the overall curve will be affected by the change. Moreover, by allowing two control points to coincide it is possible to create a curvature discontinuity. A slope discontinuity, similarly, can be introduced by choosing three successive control points to be coincident.

Some of the advantages of B-spline curves include local control over curve shape and reduced need to piece many curves together to define shape since the control points can be added at will without increasing the degree of curve.

3.3.4 NURBS and B-splines

Two important surface representation schemes exist that extend the control of shape beyond movement of control vertices. These are NURBS (Non Uniform Rational B-Splines) and B-splines. In the case of NURBS a local vertex is extended to a four dimensional co-ordinate, the extra parameter being a weight that allows subtle form of control which is different in effect to moving a control vertex.

In the simplest form of B-spline control two global parameters (bias and tension) are introduced which affect the whole curve.

3.3.5 Bezier curve

This scheme was developed by P. Bezier of the French firm Regie Renault. The advantage of Bezier curve over cubic spline curve is that the direction of the curve at the joins can be defined and changed simply by specifying the position of the control point. The change in control points not only affects the shape of the curvature near the control points but has the influence throughout the curve.

Properties of Bezier curve:

1. It passes through first and last control points. If the first and last control points coincide, the curve is closed.

2. The curve is tangent to the corresponding edge of control points at the end points.

3. Bezier curve will remain in the convex of the polygon. This is called convex hull property.

4. Bezier curve does not oscillate. This is called variation diminishing property.

5. It requires less calculations and memory compared to cubic spline curves.

6. Bezier curve is independent of the coordinate system used to measure the location of the control point (i.e Aix independence)

7. The curve do not provide local control. This means, moving any control point changes the shape of every part of the curve.

Mathematically, Bezier curve is defined as

$$P(t) = \sum_{i=0}^{n} B_i J_n, i(t)$$

Where J_n, $i(t)$ is the blending function, and is given by the relation

$$J_n = {}^nC_i t^i (1-t)^{n-i}$$

and ${}^nC_i$ is the binomial coefficient, ${}^nC_i = \frac{n!}{i!(n-1)!}$

If the three-dimensional location of control point B_i is (x_i, y_i, z_i), a vector equation can be expressed by writing equation for x, y and z parameter function separately as

$$x(t) = \sum_{i=0}^{n} x_i J_n, i(t)$$

$$y(t) = \sum_{i=0}^{n} y_i J_n, i(t)$$

$$z(t) = \sum_{i=0}^{n} z_i J_n, i(t)$$

Example

Generate a Bezier curve using the following control points: (2, 0), (4, 3), (5, 2), (4, -2), (5, -3) and (6, -2).

Solution

There are 6 control points. Thus n = 6 – 1 = 5

$$P(t) = \sum_{i=0}^{n} B_i J_n, i(t)$$

$$= \sum_{i=0}^{n} B_i \, {}^nC_i t^i (1-t)^{n-i}$$

For the x and y coordinates, parameter functions can be defined as

$$x(t) = \sum_{i=0}^{5} x_i \, {}^5C_i t^i (1-t)^{5-i}$$

$$y(t) = \sum_{i=0}^{5} y_i \, {}^5C_i t^i (1-t)^{5-i}$$

On expansion, the above equations can be written as:

$$x(t) = x_0 \, {}^5C_0 t^0 (1-t)^5 + x_1 \, {}^5C_1 t^1 (1-t)^4 + x_2 \, {}^5C_2 t^2 (1-t)^3 + x_3 \, {}^5C_3 t^3 (1-t)^2$$
$$+ x_4 \, {}^5C_4 t^4 (1-t)^1 + x_5 \, {}^5C_5 t^5 (1-t)^0$$

$$x(t) = (1-t)^5 x_0 + 5t(1-t)^4 x_1 + 10t^2 (1-t)^3 x_2 + 10t^3 (1-t)^2 x_3$$
$$+ 5t^4 (1-t) x_4 + x_5 t^5$$

Similarly,

$$y(t) = (1-t)^5 y_0 + 5t(1-t)^4 y_1 + 10t^2 (1-t)^3 y_2 + 10t^3 (1-t)^2 y_3$$
$$+ 5t^4 (1-t) y_4 + y_5 t^5$$

But

$(x_0, y_0) = (2, 0)$, $(x_1, y_1) = (4, 3)$

$(x_2, y_2) = (5, 2)$, $(x_3, y_3) = (4, -2)$

$(x_4, y_4) = (5, -3)$, $(x_5, y_5) = (6, -2)$

The above equations can be simplified to the following form:

$$x(t) = 2(1-t)^5 + 20t(1-t)^4 + 50t^2 (1-t)^3 + 40t^3 (1-t)^2$$
$$+ 25t^4 (1-t) + 6t^5$$

Similarly

$$y(t) = 15t(1-t)^4 + 20t^2 (1-t)^3 - 20t^3 (1-t)^2 - 15t^4 (1-t) - 2t^5$$

Assignment

Generate a three-dimensional Bezier curve using the following control points

(5, 4, 2), (6, 2, 3), (5, -2, 4) and (6, -4, 3)