1989

Integration of computer-aided design techniques into the mechanical product development process

Gerard R. Sturnick

Follow this and additional works at: http://scholarworks.rit.edu/theses

Recommended Citation

This Thesis is brought to you for free and open access by the Thesis/Dissertation Collections at RIT Scholar Works. It has been accepted for inclusion in Theses by an authorized administrator of RIT Scholar Works. For more information, please contact ritscholarworks@rit.edu.
INTEGRATION OF
COMPUTER-AIDED DESIGN TECHNIQUES INTO THE
MECHANICAL PRODUCT DEVELOPMENT PROCESS

by
Gerard R. Sturnick

A Design Thesis Submitted in Partial Fulfillment of the Requirements for the Degree of MASTER OF SCIENCE in Mechanical Engineering

Approved by:

Prof. [Name Illegible] (Thesis Advisor)

Prof. ________________________________

Prof. ________________________________

Prof. ________________________________

Prof. P. Marletkar (Department Head)

DEPARTMENT OF MECHANICAL ENGINEERING
COLLEGE OF ENGINEERING
ROCHESTER INSTITUTE OF TECHNOLOGY
ROCHESTER, NEW YORK
JANUARY, 1989
TITLE OF THESIS: INTEGRATION OF COMPUTER-AIDED DESIGN TECHNIQUES INTO THE MECHANICAL PRODUCT DEVELOPMENT PROCESS

I, GERARD R. STURNICK, HEREBY DENY PERMISSION TO THE WALLACE MEMORIAL LIBRARY OF RIT TO REPRODUCE MY THESIS IN WHOLE OR IN PART WITHOUT MY EXPLICIT WRITTEN PERMISSION.

I CAN BE REACHED AT THE FOLLOWING ADDRESS:

590 SENECA ROAD
ROCHESTER, NY 14622
ABSTRACT

Computer-Aided Design (CAD) has been called the most significant advance since the development of electricity. CAD is regarded as being the greatest breakthrough of modern times in the search for ways to improve the Product Development Process. This improvement is provided in terms of bringing to market better quality and higher performance products in a significantly shorter design/development cycle and at a lower cost.

A survey of the various computer-aided design techniques is presented as they are currently being applied in the mechanical product development process. The research of these techniques includes the basic system operation from a user’s perspective, as well as discussion of the relative productivity improvements possible as compared with prior techniques and alternative approaches.

The survey results are then enhanced through a case study of the more widely used CAD techniques available to a product design engineer. A typical benchmark part design of a thermoplastic clutch pawl was created and analyzed on some of the latest commercially available computer-aided design systems. This case study, conducted at Xerox Corporation, consisted of both wire frame, surface and solids geometry model creation, mass properties analysis, and finite element model structural analysis.
# TABLE OF CONTENTS

List of Figures ............................................................... iv  
List of Symbols / Acronyms ................................................. vii  

I. Introduction ........................................................................ 1  
   1.1 Definition of Key Terms ............................................. 2  
   1.2 CAD Survey Background ............................................. 3  
   1.3 Case Study Background .............................................. 4  

II. Historical Review .......................................................... 5  

III. Survey of Computer-Aided Design Techniques ...................... 8  
   3.1 Automated Drafting Techniques ................................... 9  
   3.2 Geometric Modeling Techniques ................................. 13  
      3.2.1 Wire Frame ..................................................... 15  
      3.2.2 Surface Modeling ............................................. 17  
      3.2.3 Solids Modeling .............................................. 21  
   3.3 Design Analysis Techniques ....................................... 26  
      3.3.1 Interference Analysis ........................................ 27  
      3.3.2 Mechanical Properties Analysis ......................... 31  
      3.3.3 Finite Element Analysis .................................... 33  
      3.3.4 Mechanism Analysis ........................................ 37  
      3.3.5 Miscellaneous Customized CAD Tools .................. 42  

IV. Case Study of Computer Aided Design Techniques .................... 55  
   4.1 Benchmark Part Description ...................................... 56  
   4.2 Applicon CAD System ............................................... 59
<table>
<thead>
<tr>
<th>Section</th>
<th>Title</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>4.2.1</td>
<td>Hardware Description</td>
<td>59</td>
</tr>
<tr>
<td>4.2.2</td>
<td>User Interface</td>
<td>61</td>
</tr>
<tr>
<td>4.2.3</td>
<td>Geometry Creation</td>
<td>69</td>
</tr>
<tr>
<td>4.2.4</td>
<td>Mechanical Properties Analysis</td>
<td>77</td>
</tr>
<tr>
<td>4.3</td>
<td>Intergraph CAD System</td>
<td>79</td>
</tr>
<tr>
<td>4.3.1</td>
<td>Hardware Description</td>
<td>79</td>
</tr>
<tr>
<td>4.3.2</td>
<td>User Interface</td>
<td>82</td>
</tr>
<tr>
<td>4.3.3</td>
<td>Geometry Creation</td>
<td>87</td>
</tr>
<tr>
<td>4.3.4</td>
<td>Mechanical Properties Analysis</td>
<td>103</td>
</tr>
<tr>
<td>4.4</td>
<td>PDA Engineering/Patran-G Software System</td>
<td>106</td>
</tr>
<tr>
<td>4.4.1</td>
<td>Hardware Description</td>
<td>106</td>
</tr>
<tr>
<td>4.4.2</td>
<td>User Interface</td>
<td>106</td>
</tr>
<tr>
<td>4.4.3</td>
<td>Geometry Creation</td>
<td>110</td>
</tr>
<tr>
<td>4.4.4</td>
<td>Finite Element Analysis</td>
<td>117</td>
</tr>
<tr>
<td>V.</td>
<td>Discussion</td>
<td>131</td>
</tr>
<tr>
<td>5.1</td>
<td>Comparison of Case Study CAD Systems</td>
<td>132</td>
</tr>
<tr>
<td>5.1.1</td>
<td>User Interface</td>
<td>133</td>
</tr>
<tr>
<td>5.1.2</td>
<td>System Capabilities</td>
<td>137</td>
</tr>
<tr>
<td>5.2</td>
<td>Progression of CAD Since the Case Study</td>
<td>140</td>
</tr>
<tr>
<td>5.2.1</td>
<td>General Industry Progression</td>
<td>141</td>
</tr>
<tr>
<td>5.2.2</td>
<td>Intergraph Progression</td>
<td>144</td>
</tr>
<tr>
<td>VI.</td>
<td>Conclusions</td>
<td>149</td>
</tr>
<tr>
<td></td>
<td>References and Bibliography</td>
<td>165</td>
</tr>
<tr>
<td></td>
<td>Appendix I - Applicon Mass Properties Graphics</td>
<td>A-1</td>
</tr>
<tr>
<td></td>
<td>Appendix II - Intergraph Mass Properties Graphics</td>
<td>A-2</td>
</tr>
</tbody>
</table>
## LIST OF FIGURES

<table>
<thead>
<tr>
<th>Section</th>
<th>Title</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>3.1.1</td>
<td>Automated Drafting Productivity Characteristics</td>
<td>14</td>
</tr>
<tr>
<td>3.3.1</td>
<td>Standard Type Decision Screen Menu</td>
<td>45</td>
</tr>
<tr>
<td>3.3.2</td>
<td>Preferred Hardware Screen Menu</td>
<td>46</td>
</tr>
<tr>
<td>3.3.3</td>
<td>Preferred Hardware Help Screen</td>
<td>47</td>
</tr>
<tr>
<td>3.3.4</td>
<td>Preferred Mechanical Component Screen Menu</td>
<td>48</td>
</tr>
<tr>
<td>3.3.5</td>
<td>Ball Bearing Component Menu</td>
<td>49</td>
</tr>
<tr>
<td>3.3.6</td>
<td>Mechanical Design Selection Screen Menu</td>
<td>50</td>
</tr>
<tr>
<td>3.3.7</td>
<td>Compression Spring Design Menu</td>
<td>51</td>
</tr>
<tr>
<td>3.3.8</td>
<td>Compression Spring Output Example</td>
<td>52</td>
</tr>
<tr>
<td>3.3.9</td>
<td>Gear Design Menu</td>
<td>53</td>
</tr>
<tr>
<td>3.3.10</td>
<td>Pulley Belt Design Menu</td>
<td>54</td>
</tr>
<tr>
<td>4.1.1</td>
<td>Benchmark Part Detail Drawing</td>
<td>57</td>
</tr>
<tr>
<td>4.1.2</td>
<td>Benchmark Part Material Property Table</td>
<td>58</td>
</tr>
<tr>
<td>4.2.1</td>
<td>Applicon Workstation</td>
<td>60</td>
</tr>
<tr>
<td>4.2.2</td>
<td>Applicon Alphanumeric Keyboard</td>
<td>62</td>
</tr>
<tr>
<td>4.2.3</td>
<td>Applicon Function Keyboard</td>
<td>63</td>
</tr>
<tr>
<td>4.2.4</td>
<td>Applicon Table Menu</td>
<td>65</td>
</tr>
<tr>
<td>4.2.5</td>
<td>Applicon Electronic Pen Operation</td>
<td>66</td>
</tr>
<tr>
<td>4.2.6</td>
<td>Applicon Pen Symbols</td>
<td>68</td>
</tr>
<tr>
<td>4.2.7</td>
<td>Applicon Clutch Pawl 3-D Wireframe Model</td>
<td>74</td>
</tr>
<tr>
<td>4.2.8</td>
<td>Applicon Clutch Pawl Constructed Hidden LineView</td>
<td>76</td>
</tr>
<tr>
<td>4.2.9</td>
<td>Applicon Clutch Pawl Mass Properties Elements</td>
<td>78</td>
</tr>
</tbody>
</table>
**LIST OF FIGURES**

(continued)

<table>
<thead>
<tr>
<th></th>
<th>Description</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>4.3.1</td>
<td>Intergraph Workstation</td>
<td>81</td>
</tr>
<tr>
<td>4.3.2</td>
<td>Intergraph Alphanumeric Keyboard</td>
<td>83</td>
</tr>
<tr>
<td>4.3.3</td>
<td>Intergraph Cursor Pad</td>
<td>84</td>
</tr>
<tr>
<td>4.3.4</td>
<td>Intergraph Mechanical Design Command Menu</td>
<td>86</td>
</tr>
<tr>
<td>4.3.5</td>
<td>Intergraph Design Surface Matrix Menu</td>
<td>90</td>
</tr>
<tr>
<td>4.3.6</td>
<td>Intergraph Clutch Pawl Transparent Surface Model</td>
<td>94</td>
</tr>
<tr>
<td>4.3.7</td>
<td>Intergraph Clutch Pawl 3-D Wireframe Model</td>
<td>95</td>
</tr>
<tr>
<td>4.3.8</td>
<td>Intergraph Hidden Line Screen Menu</td>
<td>98</td>
</tr>
<tr>
<td>4.3.9</td>
<td>Intergraph Clutch Pawl Hidden Line Plot - No Mesh</td>
<td>99</td>
</tr>
<tr>
<td>4.3.10</td>
<td>Intergraph Clutch Pawl Hidden Line Plot - Mesh</td>
<td>100</td>
</tr>
<tr>
<td>4.3.11</td>
<td>Intergraph Clutch Pawl - Color Shaded Image</td>
<td>101</td>
</tr>
<tr>
<td>4.3.12</td>
<td>Intergraph Mechanical Design Dimensioning Matrix Menu</td>
<td>102</td>
</tr>
<tr>
<td>4.3.13</td>
<td>Intergraph Mechanical Properties Matrix Menu</td>
<td>104</td>
</tr>
<tr>
<td>4.4.1</td>
<td>Patran-G Menu Hierarchy</td>
<td>108</td>
</tr>
<tr>
<td>4.4.2</td>
<td>Patran-G Keyboard Cursor Control Diagram</td>
<td>109</td>
</tr>
<tr>
<td>4.4.3</td>
<td>Patran-G Clutch Pawl Transparent Solid Model</td>
<td>113</td>
</tr>
<tr>
<td>4.4.4</td>
<td>Patran-G Clutch Pawl Hidden Line Plot - 30% Shrink</td>
<td>115</td>
</tr>
<tr>
<td>4.4.5</td>
<td>Patran-G Clutch Pawl Hidden Line Plot - Color Shaded</td>
<td>116</td>
</tr>
<tr>
<td>4.4.6</td>
<td>Patran-G Clutch Pawl Finite Element Model</td>
<td>121</td>
</tr>
<tr>
<td>4.4.7</td>
<td>Patran-G Clutch Pawl Deformed Geometry Plot</td>
<td>125</td>
</tr>
<tr>
<td>4.4.8</td>
<td>Patran-G Clutch Pawl Stress Contours - Isometric View</td>
<td>126</td>
</tr>
<tr>
<td>4.4.9</td>
<td>Patran-G Clutch Pawl Stress Contours - Multiple View</td>
<td>127</td>
</tr>
</tbody>
</table>
LIST OF FIGURES
(continued)

4.4.10  Patran-G Clutch Pawl Stress Contours - High Stress ............ 128
4.4.11  Patran-G Clutch Pawl Stress Contours - Sectional View ........ 129
4.4.12  Patran-G Clutch Pawl Element Identification Plot ............... 130
5.2.1   CAD Usage Survey Results ..................................... 143
6.1.1   Product Development Process Matrix .............................. 151
6.1.2   Product Life Cycle Costs vs. Time ............................... 152
6.1.2   CAD Time/Cost Impacts vs. Manual Methods .................... 161
<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Full Form</th>
</tr>
</thead>
<tbody>
<tr>
<td>B-rep</td>
<td>Boundary Representation</td>
</tr>
<tr>
<td>CAD</td>
<td>Computer-Aided Design</td>
</tr>
<tr>
<td>CADD</td>
<td>Computer-Aided Design and Drafting</td>
</tr>
<tr>
<td>CAE</td>
<td>Computer-Aided Engineering</td>
</tr>
<tr>
<td>CAM</td>
<td>Computer-Aided Manufacturing</td>
</tr>
<tr>
<td>CG</td>
<td>Computer Graphics</td>
</tr>
<tr>
<td>CIM</td>
<td>Computer Integrated Manufacturing</td>
</tr>
<tr>
<td>CRT</td>
<td>Cathode Ray Tube</td>
</tr>
<tr>
<td>CSG</td>
<td>Constructive Solid Geometry</td>
</tr>
<tr>
<td>FEA</td>
<td>Finite Element Analysis</td>
</tr>
<tr>
<td>FEM</td>
<td>Finite Element Model</td>
</tr>
<tr>
<td>I/EMS</td>
<td>Intergraph / Engineering Modeling System</td>
</tr>
<tr>
<td>IGES</td>
<td>Initial Graphics Exchange Specification</td>
</tr>
<tr>
<td>I/O</td>
<td>Input / Output</td>
</tr>
<tr>
<td>LSI</td>
<td>Large Scale Integration</td>
</tr>
<tr>
<td>MIT</td>
<td>Massachusetts Institute of Technology</td>
</tr>
<tr>
<td>NC</td>
<td>Numerical Control</td>
</tr>
<tr>
<td>NURB</td>
<td>Non-uniform rational B-spline</td>
</tr>
<tr>
<td>PC</td>
<td>Personal Computer</td>
</tr>
<tr>
<td>2D</td>
<td>Two Dimensional</td>
</tr>
<tr>
<td>3D</td>
<td>Three Dimensional</td>
</tr>
</tbody>
</table>
I. INTRODUCTION

The objective of this work is to investigate the integration of Computer-Aided Design (CAD) techniques in the mechanical product development process. Two basic approaches were employed in this investigation. The first step involved a literature search to briefly survey the extensive list of CAD techniques available today. This step was then followed by a case study to complement this knowledge base with "hands on" experience.

This chapter will provide a brief definition of key terms, as well as a general description of content and methodology utilized in the two phases of this investigation. Due to the rapidly changing nature of CAD, the timeframe of the investigation is also discussed.

Though every attempt has been made to provide an objective analysis, one needs to recognize this investigation represents a user's perspective. User in this statement is most accurately defined as a mechanical product design engineer or manager.
1.1 Definition of Key Terms

In recent years, a variety of acronyms and interpretations have been adopted for referring to the use of computerized systems in the areas of drafting, design, engineering, and manufacturing. In order to clarify the use of the acronym "CAD" in this paper the following distinction is made.

"Computer-Aided Drafting" is the use of computer, software, and associated hardware to produce drawings that would normally be prepared manually. This can be thought of as automated drafting. "Software" refers to the chained statements, directions or procedures used by the computer to perform a task, where "Hardware" is all physical equipment or devices associated with the operation of a computer.

"Computer-Aided Design" is different from the meaning of computer-aided drafting. The major difference between the two is in the software. A computer-aided design system can perform automated drafting but, in addition, it also uses the computer for designing and analyzing through the use of computer graphics. A design system today typically has design analysis functions such as finite element analysis, mass properties calculations, and three-dimensional drawing capabilities. Throughout this paper, the abbreviation CAD appears many times, and is used to refer to this definition of computer-aided design.
1.2 CAD Survey Background

Computer-aided design as a whole is an area making very fast progress and it is not easy for anyone, including experts, to keep abreast of the frontiers of its applications. Therefore, a number of information sources were utilized to develop this survey of the various CAD techniques available in the mechanical product design environment. These sources include an extensive literature search in terms of the great number of books, journals, magazine articles, and papers published over the past five years on the topic. This information base was then supplemented with applications information and experience gained as an advanced product design manager at Xerox Corporation. The intent of the survey is to provide a representative cross-section of the more commonly used CAD techniques as they are currently being utilized in new product development.

Due to the great number of CAD tools which are to be covered in the survey the scope of the investigation is limited to the basic operation, productivity gains, and comparison with prior techniques. No attempt will be made to explain the inner workings of the hardware, software, or analytical procedures on which these techniques are based. Where ever possible, figures and sample outputs are used to illustrate the CAD tools being discussed.
1.3 Case Study Background

To more completely investigate the primary CAD tools a case study is conducted on a typical benchmark part design at Xerox Corporation. The benchmark part selected is a thermoplastic clutch pawl. This case study provides a "hands on" experience of computer-aided design and drafting (CADD) and Finite Element Analysis (FEA) techniques from instruction to application. It is geared toward achieving an overall level of understanding and proficiency that the modern design engineer should obtain in order to deal with the accelerating productivity demands.

Inclusive in this study is two-dimensional wire frame, three-dimensional wire frame, surface, and solids geometry creation for the benchmark part design. Computer-aided engineering techniques were then applied utilizing the appropriate design data base to determine the mass properties, stress contours, and deflections of the part.
II. HISTORICAL REVIEW

The past few decades have witnessed extraordinary technological changes in the field of interactive Computer Graphics (CG). The capability to display computer-generated graphic forms on the screen was achieved in the 1950's at the Massachusetts Institute of Technology (MIT). This accomplishment created imagery using Cathode Ray Tube (CRT) screen technology [1].

The field of modern computer graphics began in 1963 with the sketchpad project of Ivan Sutherland [2], then a doctoral student at MIT. Sutherland's work presented an interactive drawing system incorporating the use of a CRT display unit and a light pen. Later in 1963, T. E. Johnson introduced a version of the sketchpad to draw multi-views and perspective views of an object. In Johnson's program when an operator made changes in one of the views, corresponding changes would automatically occur in the other views.

The concept of CAD showed enormous potential. A number of large industries, such as the automotive, aerospace, and defense industries, initiated or assisted in CAD research and development. The General Motors Research Laboratories, from the early 1960's, was seeking to develop computer-aided automobile design capabilities [3]. General Motors research aimed at developing an interactive method to simulate the arrangement of the components in an automobile, and to check for interference and clearance between adjacent parts. This capability would prove crucial in achieving efficiency and functionality in design. The Boeing Commercial Airplane
Company and the Lockheed-Georgia Company were also among the pioneers in the application of computer-aided design.

In spite of all these developments, many barriers inhibited the widespread adoption of CAD until the 1970's. It was then that the display technology underwent rapid changes. Vector Refresh Display Systems available in the early 1960's required the use of a very expensive and sophisticated display buffer and display processor. In the late 1960's, a new display technology, named Direct-View Storage Tube (DVST), was introduced by Tektronix. This new method of screen imagery did not require the use of expensive components as did the Vector Refresh technique.

In the 1970's, thanks to the affordability of solid state memory, Raster Display became available. This technology lowered the cost of display systems as it added to their capability.

Further software advancement was also required to provide for better and more complete application programs to satisfy the requirements of the design engineering industries. A need to write device-independent software also existed. These developments meant that a particular software could be used with several types or brands of display devices.

Another major milestone in the history of CAD development came with the use of minicomputers and microcomputers based on Large Scale Integration (LSI) technology[4]. Microprocessors and intelligent terminals provided for
better use of the central computer. This means that such a device as the CRT display may include its own processor and perform certain functions independent of the central computer. The result is more flexibility in CAD operations and greater speed in the use of the system.

Today CAD systems may be based upon any size computer. This includes the mainframe computer, minicomputer or microcomputer. A variety of software, hardware, and turnkey systems are available from which to choose. It should be noted that the foregoing factors have led to a variety of systems within a wide price range. Therefore, some CAD systems have more capabilities than others and include additional features. Some systems are suitable only for drafting, whereas others can perform complex design analysis tasks preceding the stage of computer-aided manufacturing (CAM).
III. SURVEY OF COMPUTER-AIDED DESIGN TECHNIQUES

For the purposes of this survey, the computer-aided design techniques described in this chapter are separated into the general categories of automated drafting, geometric modeling, and design development/analysis. As was discussed in Section 1.2, this survey represents a snapshot of the current CAD techniques as they are being applied in the mechanical product development environment. The emphasis of the section is on the basic operation of these tools from a user perspective, and a comparison of these techniques relative to prior practices or alternative approaches.
3.1 Automated Drafting

The implementation of computer-aided drafting is by far the most common of the CAD techniques being applied in industry. Automating the drawing creation process represents a reasonable first step. Equipment with this sole purpose is generally inexpensive and helps speed the generation of drawings, one of the most costly and time consuming engineering activities.

Since the 1970's, when automated drafting began gaining popularity, most systems were purchased as turnkey systems. These turnkey systems come with all the hardware and software required to begin using the equipment. With the advent of drafting packages for microcomputers, many users are now building their own system from equipment and software purchased separately. The most recent trend is marked with a growth in the use of the more powerful personal computers from firms now offering full blown drafting systems based around these machines [6]. The systems are designed mainly as entry level systems for firms which can not justify large sums of money for the more elaborate CAD systems. In any case, automated drafting systems require little or no knowledge of computers or programming on the part of the user to operate.

Hardware for a typical automated drafting system includes a micro or minicomputer, CRT terminal or monitor, and a plotter. Software for most automated drafting is usually restricted to 2D applications. Some packages offer color to help differentiate between different types of data. Though 3D
geometric modeling is not discussed until Section 3.2, a few drafting packages which offer 3D design capability can be converted into 2D drawings [7].

Basic operation centers around the user communicating with the system interactively through graphics. The points, lines, and arcs that comprise a drawing are entered into the automated drafting system through any number of input devices. A set of cross-hairs is commonly used to indicate points from which all elements are made. The drawing process is aided by a function menu; which puts the system into different modes to construct basic elements with minimal user input. For example, a rectangle can be defined by a corner point and its diagonal or three corner points. Circles can be drawn by several methods, including center and radius, three points on the circumference, or a specified center and tangent to a line. Exact coordinates can also be inputed via the keyboard. These functions permit drawings to be made with great accuracy, with circles and arcs blending smoothly into lines intersecting exactly.

Most systems provide a number of ways to edit or change the drawing once it is entered into the computer. A line editor can delete, extend or shrink lines. A point editor moves points, makes lines parallel, or makes lines intersect with another line or arc. A "fence", or "window", can also be drawn on the screen, with all objects within the fence being deleted, copied, or moved as specified by the operator. Objects can also be interactively moved or "dragged" on the screen. Copy functions also permit objects to be copied anywhere else on the drawing. Most systems allow the user to define symbols
and place them in the drawing as desired. These so called symbol or component libraries can be created for such things as standard hardware.

Element creation and placement may be assisted by displaying a series of equally spaced points on the screen called "grids". The spacing of these grid points can be defined by the user or made as a default value. The grid helps draw straight lines and gives the operator a feeling for scale. A related function is called "snap", in which entered points locate at the nearest grid point. The snap function can be turned on or off, depending on what the operator is doing.

Drawing on the graphics display is made easier by various view manipulation functions. For example, a particular area can be seen in greater detail by "zooming" in on a specified area. This function can be controlled in several ways, including a percentage zoom or zoom within a defined window. A drawing can also be moved horizontally or vertically by a "panning" function. This, too, is controlled in several ways. The pan can be for a specific length and direction, or to center a specific point in the screen..

Most systems automate the dimensioning required in the creation of a drawing. Through menu commands the user can have the system compute and display the distances or angles in the appropriate locations. Text can also be placed on the drawing, usually through the alphanumeric keyboard. Several fonts are typically available, and characters can be displayed in a range of sizes and angles. The text can be centered, justified right or left, or
can even be positioned on an irregular curve or angle. Text can be located by defining a single point on the drawing.

Another important feature offered on some systems is that of drawing level separation. This function helps simplify creation of the drawing and makes viewing or plotting easier because levels can be made selectively visible or hidden, or can be depicted with different colors. For example, an assembly can be separated by levels for each individual component it is comprised of. This is also helpful in decreasing the complexity of the drawing being viewed by turning off levels selectively.

Most engineering drafting packages have dozens of other functions to ease the task and capitalize on the strength of the computer. Examples of some of these features include automatic crosshatching, and line property option selection for width, color, dashed vs. solid styles. In addition, corners can be filleted automatically, elements can be rotated or mirrored, and arbitrary curves can be fit to a mathematical function such as a cubic spline. The list is almost endless as the application of automated drafting systems mature and the technologies improve.

A direct comparison can be made between automated drafting and manual methods. Productivity improvements of 3:1 or 4:1 are liberally quoted by the suppliers of turnkey CAD systems. Some users reportedly benefit from ratios as high as 20:1. This promise of increased engineering productivity is the primary justification for heavy investment in CAD, with most users expecting
a return on investment after only a year or two. But these figures should not necessarily be accepted at face value. CAD may indeed be more productive if utilized over its wide range of capabilities, but often when isolated only to drafting, manual methods may be faster. The simple fact is that CAD productivity depends heavily on the way it is used and the application to which it is being used.

CAD is most productive from an automated drafting sense in applications such as creating drawings with many repetitious details, changing drawings already stored in a computer data base, drawings with a large amount of dimensioning and lettering, and so forth. Figure #3.1.1 provides a more complete listing of common features of successful applications in automated drafting [9]. However, a study performed at Valtek, Inc. indicated there is no significant difference in drawing time between CAD and manual drafting for original, two dimensional drawings, regardless of complexity. In fact, this study concluded that manual drafting may be slightly faster in producing simple drawings. Therefore, some thought needs to be put into the type of applications for the automated drafting system to determine what, if any, productivity gain will be achieved.

3.2 Geometric Modeling

The most important aspect of CAD is the development of geometric models. Geometric modeling is the process of representing the physical form or shape of an object in the computer. Some geometric models may be more realistic or detailed than others. Nonetheless, a model by definition is a simplistic
### Drafting Characteristics

1. Many similar drawings with slight differences.
2. Drawings that undergo many revisions.
3. Drawings with a large amount of lettering.
4. Drawings that must be accurate.
5. Drawings with information that is currently extracted by hand and entered into a computer for other purposes.
6. Drawings prepared for several alternative proposals.
7. Complex drawings with several types of information that may be presented separately or together.
8. Drawings that present several different views of the same object.
10. Drawings that must be done quickly, even at a cost premium, because they are prerequisites for other work.
11. A work environment where shortages of qualified drafting manpower exist or where the cost of labor is unusually high.
12. Drawings that require periodic update with consistent technique over a long span of time.
13. Drawings where attractive appearance is important, such as catalog illustrations.
14. Drawings that currently are done using cut-and-paste or overlay techniques with mylar or butter paper.
15. Pictures derived from numerical origin, such as charts and graphs for business management.
16. Large amounts of visual information that must be organized, such as aerial surveys in mapping.
17. Data that can be presented graphically for better understanding and quicker recognition.
representation of a design or concept. The creation of geometric models is therefore a procedure used to construct and display the form of a design on the CRT monitor.

Geometric models are the starting point for virtually all functions in computer-aided design and manufacturing. A model can be used as the input for automatic drafting or the making of working drawings. The geometric model is also used as input to the computerized engineering analysis programs such as in the creation of finite-element models. In computer-aided manufacturing, the geometric model can be used to create numerical control (NC) instructions. These are programs that automatically run machining or cutting tools for the fabrication of the part or a tool which can be used to manufacture the part. Some of the engineering analysis functions are discussed in greater detail in Section 3.3 of this paper.

There are three methods which are used for constructing geometric models: wire frame, surface modeling, and solids modeling.

3.2.1 Wire Frame Modeling

Wire frame is a line drawing method showing only the edges of an object. Most geometric modeling today is done with wire frames. The basic CAD systems offer only this type of modeling. Simple graphic elements or entities, such as lines, arcs circles, or splines are used to show a picture of the design work. A wire frame is the simplest type of model suitable for drafting and design applications.
The basic operations used to create a wire frame model are very similar to those described in the automated drafting Section 3.1, as will be true for most of the interactive graphics operations discussed in this paper. Wire frame models are created by specifying points and lines in space. Unlike the drafting part description, the wire frame geometry is created as a three dimensional representation. To enable this, the two dimensional projected image on the interactive terminal screen is either divided into sections showing various views of the model, or specific views can be selected. Some systems use only a single view with a moveable and rotateable work place on which the points and lines lie. The operator can use the CRT in much the same manner as a drawing board to create top, bottom, side, isometric, and other views of the part. Unlike drafting, however, the CAD system provides many features to speed design. As a line is placed in the model creation it will be created in all views automatically. Therefore, the designer can work in the easiest view to construct each feature of the three dimensional model.

Many other CAD features are provided to assist in the 3D model creation as additions or enhancements to those previously discussed under automated 2D drafting. For example, due to the complexity of 3D representations, many systems offer features for the operator to limit the visible depth of the object in a view. Users can also select lines or areas of the object on the screen and temporarily erase them from the model to view more clearly the area under construction. The features of level and color separation are also key aides in the creation of the 3D wire frame models.
As compared to the other geometric modeling techniques, wire frames are generally the simplest models to create. Consequently, these stick figure structure models expend relatively little computer time and memory, and they provide precise information about the surface discontinuities on the part. Wire frames, however, contain no information about the surfaces themselves nor do they differentiate between the inside and outside of objects. Thus, wire frames can be ambiguous in representing complex physical structures and often leaves much interpretation to users. This is partly due to the fact that both visible and hidden lines of the objects are shown as solid lines. This shortfall also makes the detection of interferences in assemblies and system designs almost impossible. It is also difficult to detect impracticable designs in wire forms. In response to these difficulties, some systems provide the operator with semi-automatic hidden line removal features, but due to the inherent nature of wire forms this process is very laborious as individual lines may be visible or hidden depending on the view being observed.

Therefore, utilizing 3D wire form geometry models as a stepping stone to satisfy automated drafting and engineering analysis is far from ideal. For each application, a significant amount of user labor is required.

3.2.2 Surface Modeling
Surface models represent the next level of modeling. The creation of these models involves connecting various types of user selected surface elements to represent part geometry. The entire model may be comprised of different types of interconnecting surfaces.
Most CAD systems provide extensive surface menus from which to model. Typical surface menus include planes, tabulated cylinders, ruled surfaces, and surfaces of revolution, along with sweep, fillet, and sculptured surfaces.

A plane is the most basic surface type. The system merely creates a flat plane between two user specified straight lines which define the edges. A tabulated cylinder is the inverse projection of a free-form curve into the third dimension. Basically, this is a curved plane between two arbitrary parallel curves.

A ruled surface is produced between two different edge curves. The effect is a surface generated by moving a straight line through space with the end points resulting on the edge curves. A surface of revolution is created by revolving an arbitrary curve in a circular arc about an axis. This capability is especially useful in modeling turned parts and parts with axial symmetry. Sweep surfaces, however, sweep an arbitrary curve through another arbitrary curve instead of an arc.

The fillet surface is a cylindrical surface connecting two other surfaces in a smooth transition. This is a tedious, subjective operation that has been done manually in industry for years. But CAD systems quickly solve the problem of blending surfaces with the precise mathematical continuity required by many applications.

Sculptured surfaces are the most complex surface representation. There are many types of sculptured surfaces, including curve-mesh, free-form, B-spline,
and cubic patch surfaces. A sculptured surface is a differential surface created from two families of curves. These families are not restricted to being orthogonal, nor are the curves types fixed. Curves need not even be parallel. The two curve families intersect one another in criss-cross fashion, creating a network of inter-connecting patches. These surfaces can be represented mathematically in many ways, and most CAD modelers use a variety of representations. For instance, each automotive company standardizes around different surface representations, such as the Gordon (GM) and Chord Height Blend (Ford) surfaces. The aerospace industry uses Bezier or B-spline representations. Other common representations include the Coon's patch and the parametric cubic line, surface, or patch [11].

The latest trend in curve and surface representation has been toward the use on rational polynomial functions. Non-uniform rational B-spline (Nurb) curves and surfaces have been an Initial Graphics Exchange Specification (IGES) standard since 1983, and a number of commercial modelling systems exist that are based on rational Bezier and rational B-spline representations. This popularity is due to the fact that Nurbs offer one common mathematical form for the precise representation of standard analytical shapes (lines, conics, circles, planes, and quadratic surfaces) as well as free-form curves and surfaces. They also offer extra degrees of freedom (the weights), which can be used to generate a large variety of shapes, and are genuine generalizations of non-rational Bezier and B-spline forms. Therefore, most of the well known properties and computational techniques for non-rational forms extend easily to the Nurbs [35].
Sculptured surfaces are complex contours that can not be described with the usual lines and curves of conventional modeling. Typical structures in the mechanical design environment which contain such contours range from helicopter blades and automobile bodies to camera cases and glass bottles.

When compared to other geometric modeling techniques, surface models overcome much of the ambiguity which is present with wire frame models. True automated hidden line removal can be done with surface models which is of great benefit in supporting automated drafting and part visualization. Color shading imaging is also a simple operation for the user on most of today’s CAD systems. The solid appearance which results from automated hidden line removal and color shaded imaging is of great value in part visualization. Time consuming tasks like the creation of explored assembly drawings and creation of service documentation can be done with much greater ease by using the surface model data base. In addition, surface models provide a precise definition of the outside part geometries and help produce NC machining instructions where the definition of structure boundaries is critical.

One must keep in mind though that surface models only represent an envelope of the part geometry. They do not provide enough definition to support mass properties analysis, finite element model creation, or cut away views. They also require more computer time and memory to develop and can tend to slow down the system. Other concerns relate to the additional time it
takes to construct and change this more complicated model. Due to these shortcomings, many users combine surfaces for detailed faces with wire frames representing the rest of the part. Many CAD vendors are aggressively pursuing software and hardware solutions to these problems.

3.2.3 Solids Modeling

Solids modeling is the highest level of sophistication in geometric modeling. Solids modeling techniques completely define the external and internal geometry of a part. Unlike the other geometric modeling approaches, solid models hold the potential to create a base of data that provides a complete description of the part to all other downstream applications.

The basic operations on which most solid modeling programs are based use one or both of the following construction techniques: Constructive Solid Geometry (CSG) and Boundary Representation (B-rep).

In the CSG approach, models are constructed by combining simple shapes, such as cubes and cylinders, in building block fashion. These so called primitives are combined by a mathematical set of Boolean or logical operators of union, intersection, or difference. The user positions primitives as required and then enters the proper logic command to produce the required shape. For example, a round hole may be produced in a part by subtracting a cylinder from the geometry. With these successive operations, the user constructs a complex model.
Most commercial CSG modelers contain twelve or more basic shapes. But the four most commonly used are the block, cylinder, cone, and sphere. These so-called natural quadratics represent the types of surfaces produced by rolling, milling, turning, cutting, drilling, and other general machining operations used most commonly in the industry. As a result, primitives can be used to model most industrial parts. Geometry with sculptured surfaces and other complex contours, however, require extensive interaction and consume large amounts of computer time to construct using the CSG method. Parts in this category include automobile exhaust manifolds, aircraft flight surfaces, and hand tool housings.

Parts with complex shapes such as these are more readily modeled with the boundary representation approach. In this method, a solid object is represented by its spatial surface boundary. Techniques to define this boundary typically include several types of sweeping operations in which a two-dimensional surface is moved through space to trace out a volume. For example, a surface may undergo a linear sweep operation to produce an "extruded" part with constant thickness. Or a surface may be revolved about an axis to create a "turned" part with axial symmetry. In a variation of these techniques, a surface may be swept through a specified curve to generate a more complex solid.

Another B-rep construction technique is called gluing. This is a method where two previously created solids are joined at a common surface to produce a new unified object. And a technique called tweaking makes local changes to
an overall shape. Boolean operations can also be used in a manner similar to that of primitive modeling to unite, intersect, and subtract solids.

Both the constructive solid geometry and boundary representation methods of solid modeling have advantages and disadvantages. As a result, considerable research is aimed at developing solid modeling software that combines these two methods and indeed some of the advanced programs integrate the two approaches into a unified package.

Unlike wire frame and surface models, solid models can determine if a specified point lies inside, outside, or on the surface of the part. In fact, this test is commonly used to determine whether or not a program is truly a solid modeler.

Both CSG and B-rep have advantages in modeling certain geometrics. Due to the nature of CSG, in terms of closely simulating general machining operations, most industrial parts are more readily modeled using this approach. In addition, solids are most often represented with fewer parameters with CSG than with B-rep. For example, a cube is represented by CSG with only 12 parameters (the x, y, z coordinates for each of the corners) as opposed to the B-rep approach that defines 6 faces, 12 edges, and 8 vertices.

The primary advantage of the B-rep modelers is the wider range of geometries they can readily depict, since they are not limited to the primitive shapes of CSG systems. Another advantage is that the surface boundary of the solid is
stored explicitly in the computer and therefore does not need to be extracted from the model as with CSG systems. As a result, B-rep models are more readily converted to wire frames. Similarly, transferring wire frame data to a B-rep system is simplified.

The inherent strengths and weaknesses of CSG and B-rep systems have led to the development of so-called Hybrid systems that combine features of both approaches. In fact, no commercial system is purely one type or another, and the differences between the two categories are becoming less distinct as solid modeling technology becomes more refined. For example, most B-rep systems have Boolean operations for combining models. Similarly, some CSG packages have implemented sweep techniques for generating user defined primitives. In addition, many CSG programs use the primitive building block technique to construct the model but convert it to boundary representation for storage and manipulation in the computer.

When compared with the other modeling techniques, solids are described as the wave of the future in computer graphics, and the key to overall integration of CAD and CAM. While conventional wire frame and surface models represent only edges and envelopes of a geometry, solid models precisely define the material inside the part. This representation eliminates any ambiguity in interpreting the model and provides a more complete data base for performing a range of other functions.
Some additional functions provided by solid modelers include computing mass properties, checking for interferences in both static and kinematic studies, creating finite element models, and automatically producing NC instruction. But perhaps the most striking feature of solid modeling is the ability to produce pictures of photographic quality. In fact, the ability to produce color-shaded images is often mistakenly used as a primary criterion for determining whether a program is a solid modeler. This criterion is inappropriate since most surface modelers, as discussed in the previous section, can now readily produce the same realistic display. Though one main difference which solids modelers provide relative to visualization capability is in viewing the internal part details such as displayed in cut-a-way views. In this sense, a more suitable criterion for determining if a program is a solid modeler is if it can determine whether or not a specified point lies inside, outside, or on the surface of a part.

Solid modeling, however, is still in its infancy. Most solid modeling programs in 1980 were still in prototype development at universities and research institutions. And the few commercially available programs at that time were expensive, cumbersome to use, ran in batch mode, and operated only on large in-house computer systems [12]. As a result, the use of solid modeling packages was largely restricted to large corporations that purchased the programs more for evaluation and research than practical use.

Today, the use of solid modeling has increased sharply due to reduced computing cost, interactive user interfaces, and software improvements [10].
Moreover, a rapidly growing number of commercial programs are available. These packages are less expensive than their predecessors and can be easily implemented on minicomputer-based graphics systems. In addition, today's software constructs models in far less time and with less difficulty than earlier programs. Consequently, solid modeling is becoming increasingly practical for a broad range of tasks in design and manufacturing. As this technology continues to grow it promises to become the predominant method of geometric modeling and a primary tool for the largest group of potential users, mechanical engineers.

3.3 Design Development/Analysis Techniques

Once a geometric model has been created, the mechanical product design engineer turns his attention to the analysis and refinement of a virtual part. This allows for faster and more flexible manipulation and study than is possible with the physical part. Traditional methods which required actually building a series of physical prototypes of the design and its refinements and testing them can be streamlined through the utilization of the computer-aided design, development, and analysis techniques.

Another key benefit which the computer brings to the mechanical product development process is that of quality. In today's highly competitive environment not only is the cost and time to deliver a product to the marketplace important, but there is also more pressure on such areas as reliability, safety, energy efficiency, appearance, and low cost to the
consumer. The rapid growth of CAD as a discipline indicates the necessity of using the computer as a partner to assist in the design development process.

This section deals with the most common design development and analysis techniques which are being applied today. In addition, Section 3.3e deals with a variety of customized design aides to illustrate how CAD systems can be utilized to support certain industry specific applications.

3.3.1 Interference Analysis

The advantages of CAD systems to visualize becomes very pronounced when three dimensions are involved. Three dimensional design has always been a particularly difficult concept for the human brain to grasp. Traditional engineering methods typically involved the creation and transfer of 3D abstract ideas by rendering them on a flat 2D sheet of paper. This type of design representation makes the task of multiple part assembly layout and interference analysis very difficult.

The design terminal or workstation is the interface point for this activity in a CAD system. The designer, by issuing commands to the system and responding to its prompts, creates, manipulates, and refines the design. This is all done without ever having to draw lines on paper or, more significantly, without ever having to recreate an existing design element. As the design is taking shape, the CAD system accumulates and stores the part geometry, identifying precise locations, dimensions, and other attributes of every element.
Early in the design process a space management layout, commonly known as the "big picture", is typically created. The big picture is comprised of the subsystems of the product being designed. The space required by each subsystem, and the specific parts it is made up of, can be managed within a prescribed envelope to avoid interferences. As the designs change, the big picture can be automatically updated to represent the latest configuration. This data base can be used, as needed, by all designers and other personnel working on the product.

A number of features are provided on most CAD systems today to assist the operator in utilizing these complex layouts for interference analysis. The ability to assign different colors provides contrast to adjacent subsystems, parts, or areas within a part. Another visualization feature allows the line width and style to be varied. For example, a neighboring part can be depicted in thinner or dashed lines to avoid confusion.

In addition to the visual line attributes, there are a variety of viewing commands to assist the operator in analyzing interference. For instance, most systems provide the ability to segregate or group entities by "overlays," "levels", or "layers". A "layer" can be thought of as being similar to separate sheets of paper or overlays in conventional drafting terms. Most CAD systems have between 10 to 200 layers available to the user [13]. This makes it possible to turn off certain entities on the screen or in plotting for clarity. In a similar fashion, information can be separated by files and selectively
referenced along with the active design file. This allows visualization but not modification of the information in the reference file.

The added depth of 3D in the CAD system makes it easier to visualize interferences and facilitates the integration process [14]. It also makes for a very complicated layout when depicted in wire frame with all hidden lines visible. As a means of minimizing this inherent shortfall, most systems allow the user to set the display depth which is visible in any given view. These features are also complemented by user selectable viewing angles, multiple views capability, zoom selection, and a variety of other viewing options to enhance flexibility.

Measurement and calculating functions are of primary importance when determining the relative relationship between parts. Most CAD systems offer a group of functions which permit accurate values to be determined for such values as shortest distance between two elements, perimeters, relative distance between two points, etc. It is also common practice in CAD design systems to have all designs set to a consistent datum for the product. Since all design parameters are precision input, the designer can always relate the nominal position back to the universal x, y, z coordinates for the product.

CAD systems are also being used increasingly to study moving parts in equipment such as automobiles, machine tools, aircraft, robots, and home appliances [16]. Formerly, interference analysis of complex linkages could only be visualized with physical models, which are costly and time consuming
to build. Now designers can check for proper clearance within complex assemblies such as aircraft landing gears or in service tool access in an automotive engine compartment.

In such applications, an extension of this capability provided in advanced CAD systems allows for animation sequences to be developed. This not only serves as a depiction of moving parts of a mechanism in action, but also could be used to illustrate an assembly process to insure feasibility and to simplify the process.

Although interference investigation can be addressed utilizing either wire frame, surface, or solid models, the inherent limitations of each, which were highlighted in Section 3.2, need to be considered. 3D spatial relationships are not as apparent with conventional wire frame or surface models as they are with solid models. Certainly a complex, multi-part assembly depicted in a 3D wire frame is visually confusing and require the operator to spot interferences. Whereas with solid models, nominal material overlaps can be automatically detected by the system. On the other hand, the extremely high data storage and computer processing requirements for a big picture to be created and analyzed in solid form is pushing beyond the current capabilities available in most corporations today.

Therefore, even though CAD has made significant progress in the ability to detect and prevent interferences, further advancements are still expected. As software and hardware technology continues to improve, so will the efficiency
of the CAD system in providing effective interference analysis capability. It is also within reason to believe that as the drafting interface becomes linked to the geometry model, it will be possible to provide a graphical tolerance analysis illustration. This type of analysis will extend the systems' capability to consider the culmination of tolerances as they appear on the detail drawings.

3.3.2 Mechanical Properties Analysis

Often in the product development process there is a desire to determine the mechanical properties of parts and various levels of assembly up to and including the entire product. Applications for this type of information could include such things as establishing the area of a sheet metal part for cost estimation, calculating mass properties for dynamic analysis, or providing the total weight and center of gravity for a completely assembled machine.

CAD techniques which support the mechanical properties analysis typically fall into the categories of planar sectional properties and volume properties. Planar sectional properties would be used to determine the area, perimeter, centroid, principal axis, or principal moments of inertia for a user specified bounded planar region. Similarly, volume properties would be used to determine the surface area, centroid, volume, principal axes, and second moments of inertia for a user specified volume. In addition, with density input provided by the user, the respective mass properties including center of gravity, weight, and mass moments of inertia can be automatically provided.
The degree of automation provided by the CAD system in the determination of mechanical properties will differ greatly based on the type of geometric model being analyzed. For example, calculation of mass properties for a solid modeled part would only require the operator to select the menu command, select the element or group of elements to be considered, and key in the mass density of the material. Since a solid model completely describes the internal make-up of the part, the computer can automatically calculate the volume, weight, centroid, and mass moments of inertia for the user selected element. In fact, early applications of solid modeling was used primarily in a stand-alone manner to calculate mass properties [15].

Although wire frame and surface software packages initially could not provide mass properties of the parts they were used to model, they have been enhanced over the years so that they can now do most of the tasks. In order to provide the mechanical properties analysis with these modeling techniques, the user is required to provide the additional information necessary to define the internal structure of the part. For instance, to perform the sectional properties analysis requires the user to define a bounded planar region. This process typically involves the joining of all line elements which describe the outside edges of a planar surface till it is completely bounded. The user would usually do this interactively using the cursor to identify the element to be joined. In addition any holes of cut outs in this bounded planar surface would have to be identified. A bounded planar surface can then be projected or rotated to describe a volume which can be used to calculate the mass properties. This same process would have to be repeated for each bounded
planar surface which is required to adequately describe the geometry being analyzed. Most systems provide a means to sum the results from each element and recompute the properties of a body about a user selected center.

Though mechanical properties analysis can be cumbersome when utilizing wire frame or surface models on complex parts, these techniques still offer significant benefits over conventional methods. In the past a mechanical product engineer could either approximate the geometry with a series of standard shapes or build a prototype and empirically measure the mechanical properties. The CAD techniques by comparison provide more precise results with significant time savings. The computer also offers the user greater flexibility to analyze various concepts prior to moving forward on a specific design approach.

3.3.3 Finite Element Analysis

Finite Element Analysis (FEA) is a technique for determining characteristics such as deflections and stresses in a structure otherwise too complex for closed-form mathematical analysis. The structure is broken into a network of simple elements (rods, shells, or cubes depending on the geometry of the structure), each of which has stress and deflection characteristics easily defined by classical theory. Determining the behavior of the entire structure then becomes a task of solving the resulting set of simultaneous equations [19].
This network of simple elements is called a "mesh" or "grid", with elements connected at "nodes". The total pattern of elements is referred to as a "model". The total number of simultaneous equations describing the model usually is in the hundreds or thousands, and therefore can only realistically be solved by computer.

The finite element method is applicable over a wide range of mathematical problems in engineering and physics. The applications include such areas as the analysis of structures, thermal systems, fluid flow, electrostatics, compressible fluid flow, and vibrating systems [17]. This section will deal specifically with static structural analysis which is the most common of FEA types.

Static Finite Element Analysis solves for the deflections and stresses in a structure under a constant set of applied loads. The material is generally assumed to be linearly elastic, but special cases such as plastic deformation, creep, large deflections, and stress stiffening can be handled in some programs.

The first step in finite element analysis is the creation of a model that breaks a structure into simple standardized shapes, called elements, which are defined by a set of coordinate grid points. The coordinate points, called nodes, are locations in the model where output data are provided.
More than one type of element can be used in a model. These elements can be two dimensional, where all forces and displacements act in a plane. These elements can also be three dimensional solid elements, where forces and displacements act in all three directions or when a structure has complex geometry that does not allow two-dimensional analysis. There is a great variety of element types available to best suit the FEA application.

Building models solely by manual numerical data input has, until recently, been the standard way of constructing finite element meshes. But tabulating hundreds of node coordinates and element information is a tremendously error prone and time consuming task. The geometry of finite element structures often is so difficult to visualize that physical models often have had to be built. Mistakes in models built by these manual processes often can be uncovered only after hours, and sometimes days, of number crunching in the computer [18].

More recently, however, new finite element modeling (FEM) software products have been able to perform much of the modeling automatically. With the introduction of the minicomputer, software developers had enough economical computing power to allow the creation of mesh generating pre-processors. This, in turn, made finite element analysis considerably easier, since these packages allowed models to be created and edited much faster than by manual methods. Geometric modeling, automatic mesh generation, mesh copying, and element reflection capabilities allow rapid creation of nodes and elements. With interactive computer graphics, the resulting mesh is
displayed as it is being constructed. Dynamic manipulation features permit the model to be rotated, moved, or magnified for rapid examination and verification.

The most current CAD systems utilize the geometric model as the basis for the user to build the mesh. Using a so called mapped or edge-descriptor approach for mesh generation, the user segments the part into areas, or volumes for a solid model, for which a mesh density is specified. Based on this input, the system automatically generates an orderly mesh for each area.

User aides similar to those discussed in the geometry model creation are available to help in the mesh generation. For example, hidden line removal displays elements only visible on the viewable forward surfaces of the part to simplify appearance. In addition, some new features are provided which are specialized for the application. For instance, a shrink feature separates elements in order to expose inadvertent holes left in the mesh.

Meshes can also be optimized in the pre-processor in terms of compression, compaction, and connectivity. Compression deletes stray nodes produced during mesh generation but not connected to any elements. Compaction re-numbers nodes to make a contiguous set of indentifiers. And connectivity reorders the nodal number pattern so that the computer can analyze the model in the most efficient sequence that conserves processing time and memory.
Once the model is completed, nodal stiffness properties are calculated by the finite element program, and arranged in matrices within the computer. These parameters are then processed with applied loads and boundary conditions for calculation of displacements, stress, or other data specified by the program.

CAD systems have also improved the result evaluation through the use of post-processors. These routines simplify and speed interpretation of analysis by graphically displaying output data that would be virtually unintelligible in tabular form. Output display may be in the form of stress contour plots or exaggerated deflection plots to show how the structure behaves under load.

As a result of these improvements, the use of finite element analysis has grown significantly as a tool in mechanical product development. In fact, if done by a reasonably experienced user, finite element modeling is surprisingly inexpensive, especially when the cost is compared to that of weeks or months of manual modeling. Constructed manually, models with up to 500 elements might take five to ten times as long to create. Moreover, most complex models would be virtually impossible to construct manually [18].

### 3.3.4 Mechanism Analysis

Within the broad title of mechanism analysis are the two basic categories of kinematic and dynamic analysis. These types of analyses, when teamed with interactive computer graphics techniques, are providing product designers with dramatic reductions in the time required to design and analyze mechanisms. Through the use of these CAD tools, users are able to enter data
and readily view the results. Moreover, a computer can solve the equations in mechanism analysis and produce data so fast that numerous designs can be developed and compared, permitting refinement of design and evaluation of many alternatives.

Kinematic analysis is the calculation of properties of motion such as displacements, velocities, and acceleration without regard to forces for the synthesis of mechanisms required to produce the desired motion. The mathematics used to describe linkage motion is so complex that designers usually resorted to pin and cardboard models or complicated graphic constructions to develop workable mechanisms. By putting the mathematics of kinematics into software, complex mechanisms can be designed in much less time than with the manual methods. In this regard, such software can assist in creating mechanisms that work better, last longer, and cost less to manufacture.

In the past, kinematics software was used only by experts for design of critical components. Newer programs, however, look to put kinematic analysis into the mainstream of product design. These programs are easier to use and permit kinematic analysis to be done in the conceptual stages of design [15]. The intent of these programs is to allow their use by drafting designers, who are typically left with the task of resolving interference problems. In fact, some of the latest systems allow kinematics to be analyzed utilizing the geometric solid model as the base [21].
Interactive graphics is the key in achieving ease of use. Pre-processing involves the construction of the model which is built graphically on the screen, ensuring a correct representation of the parts. Libraries of joints are used to build the kinematic model to further simplify the operation. Post-processing of the results provide animation and time-slice freeze frames of the mechanism in motion. The utilization of CAD workstations typically provides improved graphic interface capability. The graphic enhancements allow the user to ensure smooth motion and to detect interferences.

Beyond analysis, some software packages can perform kinematic synthesis. This is where the computer builds a linkage mechanism based on the desired motion defined by the user. With interactive graphics, the user defines the points that a mechanism must pass through, and the program then determines the possible linkage configurations. Synthesis software is generally restricted to certain types of common mechanisms such as four bar linkages or cams. Thanks to the high powered CAD workstations, such software can now display possible linkages in real-time as the user changes the boundary conditions for the desired mechanism.

Dynamic analysis, on the other hand, differs from kinematic analysis in that it does not assume rigid members and uses all system forces and mass properties to determine velocities and accelerations. In product design, the engineer can use dynamic analysis to determine motion from the forces acting on a system. Dynamic analysis generally results in a more realistic simulation of mechanical system than kinematics. Most dynamic analysis
programs available today will solve kinematic problems as well, but software specifically designed for kinematic analysis is usually more efficient for this type of evaluation [7].

Although dynamic analysis software has been around for years, recent developments have made this tool more practical for use in the product development process. Vendors of dynamics software are improving performance of codes by emphasizing quality control, user interfaces, and integration methods [20]. To put dynamic analysis into a wider application, such programs are being integrated into CAD systems and linked with other software such as finite element analysis packages. Integrating dynamic analysis into CAD provides several benefits. This approach allows use of the common hardware and the adept user interfaces provided in the CAD systems. In addition the transition from modeling to analysis is much smoother and provides for much greater consistency in operation and data base usage. Such integration also means that dynamic analysis can be used early in the design when it can most efficiently influence the final design.

The operations used to construct the models for dynamic analysis involve the process of combining geometric data and mass properties of the structure with information about applied forces. All parts and forces that describe the mechanical system are chosen from a library of standard elements and are interactively pieced together in the computer. This definition is entered through part, joint, marker, force, and generator descriptions entered by the user at the terminal. Part statements define the geometry, mass, and
moments of inertia of each part in the structure. Joint statements describe contacts between moving parts that hold the assembly together. Joints can be specified as providing translational and rotational movement, including those of revolute, spherical, screw, universal, and cylindrical joints. Marker statements provide a point or coordinate system fixed on each part; orienting it to other parts, and together defining the overall configuration of the entire system.

Internal reaction forces in the system are selected from a library of standard force elements such as dampers and linear springs. In addition, user specified parameters can also be incorporated.

The output from the dynamic analysis includes joint forces, as well as relative displacements, velocities, and acceleration between any selected pair of points in the system. Data are typically available in tabular form as a function of time. Graphs may also be produced showing output quantities such as force versus time, or force versus displacement [7].

As with the other analysis techniques, dynamic analysis also stands to benefit from improvements in CAD workstations. Instead of stick figures used to represent models, realistic shaded images are used to display the results of dynamic analysis. Some of the latest packages now couple extensive modeling capabilities with assembly building commands and animation of results. The graphical animation permits engineers to visually and mathematically identify collisions and interferences [15].
3.3.5 Miscellaneous Customized CAD Tools

In addition to the universal analysis techniques discussed in this section, many industries are investing in a host of specialized CAD tools to support their unique product development requirements. These CAD packages provide a quick and efficient means to perform many design tasks which were previously done manually. Examples of these tasks include selecting standard parts, spring design, gear design, timing diagrams, belt length calculation, as well as very specialized applications like paper path simulation. The introduction of these and other packages allow designers and engineers to access virtually all needed design information while engaging in an interactive session of the CAD workstation.

The following is a brief summary of how some of these CAD tools are being applied at Xerox Corporation utilizing an Intergraph CAD system. In order to simplify the interface with the design packages a sequence of screen menus and prompting messages are provided. Examples of these tutorials have been included to help illustrate the basic operations from a user perspective.

In every product design environment there is a set of standard components which are available. In fact, it is very desirable to minimize the number of components used in a product design by taking advantage of standard components wherever possible. This is done to reduce inventory costs, leverage buying power, simplify service, etc. To help in achieving this objective, standard component libraries are created and made accessible from the CAD workstation by selecting the appropriate menu command. Screen
menus and prompts then lead the user through the component selection process. On-line help information is also available to assist the user as required. A sample of a standard component tutorial sequence is illustrated in Figures #3.3.1 through #3.3.5. Once the component is chosen, the program then places a copy of the component into the user’s design file.

Through a similar process, the designer or engineer can access machine element design tutorials. By selecting the computer-aided engineering (CAE) menu command, the user will bring up the design element screen menu. This category of tools could include programs to assist in various types of spring designs, belt system designs, gear designs, and so on. The user simply steps through the screen menus by interactively responding to the prompt displayed on the screen. Figures #3.3.6 through #3.3.11 illustrate a sample tutorial for the design of compression springs, gears, and belts. Results of the analysis are not only displayed on the screen, but also copied into an ASCII file for reference purposes.

Many more specialized CAD programs are also being developed by some companies to support their unique design requirements. For instance, a proprietary paper path simulation program has been developed at Xerox Corporation to assist their engineers in the design of paper handling systems for their business products. This sophisticated program provides a tutorial driven approach to interactively perform two dimensional paper path analysis. By using the geometry model from the users design file, the program can calculate the critical values like the input drive force and normal
forces necessary to pass the paper in a prescribed baffle arrangement. It also can determine the stubbing coefficient of friction and conditions for various failure modes.

The benefit of these CAD tools, and others like them, is in reducing the cost and time required to develop a product. Each of these tools help the user, specifically the mechanical engineer and designer, optimize their designs in the conceptual stages of the design process. This is extremely important as much of the design flexibility is present only in the early stages of development.
Figure #3.3.1 - Standard Type Decision Screen Menu [28]

MULTINATIONAL PREFERRED DESIGN SYSTEM

SELECT ONE:

- HARDWARE
- MECHANICAL COMPONENTS

EXIT
**PREFERRED HARDWARE 1985**

<table>
<thead>
<tr>
<th></th>
<th>SEMS MACH. SCREW</th>
<th>FLNG MACH. SCREW</th>
<th>HEX MACH. SCREW</th>
<th>HEX TAP SCREW</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>112WXXXX55</td>
<td>113W35858</td>
<td>131WXXXX53</td>
<td>153WXXXX52</td>
</tr>
<tr>
<td>THREAD ROLL SCREW</td>
<td>153WXXXX53</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>HEX TAP SCREW</td>
<td></td>
<td>156WXXXX55</td>
<td></td>
<td></td>
</tr>
<tr>
<td>THREAD ROLL SCREW</td>
<td></td>
<td>158WXXXX52</td>
<td></td>
<td></td>
</tr>
<tr>
<td>HEX MACH. SCREW</td>
<td></td>
<td></td>
<td>131WXXXX53</td>
<td>153WXXXX52</td>
</tr>
<tr>
<td>SEMS MACH. SCREW</td>
<td>112WXXXX55</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>FLNG MACH. SCREW</td>
<td>113W35858</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>HEX MACH. SCREW</td>
<td>131WXXXX53</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>HEX TAP SCREW</td>
<td>153WXXXX52</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>THREAD ROLL SCREW</td>
<td>153WXXXX53</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>HEX TAP SCREW</td>
<td>156WXXXX55</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>THREAD ROLL SCREW</td>
<td>158WXXXX52</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>HEX MACH. SCREW</td>
<td>131WXXXX53</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>HEX TAP SCREW</td>
<td>153WXXXX52</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>THREAD ROLL SCREW</td>
<td>153WXXXX53</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>HEX TAP SCREW</td>
<td>156WXXXX55</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>THREAD ROLL SCREW</td>
<td>158WXXXX52</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>HEX MACH. SCREW</td>
<td>131WXXXX53</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>HEX TAP SCREW</td>
<td>153WXXXX52</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>THREAD ROLL SCREW</td>
<td>153WXXXX53</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>HEX TAP SCREW</td>
<td>156WXXXX55</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>THREAD ROLL SCREW</td>
<td>158WXXXX52</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**IDENTIFY HARDWARE WITH DATA POINT (DB)**

PREFERRED SEMS MACH SCREW SIZES: **PICK ONE WITH A DB**

<table>
<thead>
<tr>
<th>DIAMETER &gt; LENGTH</th>
<th>M3</th>
<th>M4</th>
<th>M6</th>
<th>**</th>
<th>**</th>
<th>**</th>
</tr>
</thead>
<tbody>
<tr>
<td>ACTIVE</td>
<td>6</td>
<td>8</td>
<td>12</td>
<td>16</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

PART * = 112W27455
Figure #3.3.3 - Preferred Hardware Help Screen [28]

**HARDWARE HELP SECTION**

All hardware cell origins are on the mounting surface and are placed in the view where the mounting surface is planar to the screen.

The screws go in with the threads going into the screen with respect to the mounting surface.

The nuts go into the screen with respect to the mounting surface.

View planar to surface
Figure #3.3.4 - Preferred Mechanical Component Screen [28]

<table>
<thead>
<tr>
<th>Component</th>
<th>Number</th>
<th>Number</th>
<th>Number</th>
<th>Number</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bail Bearing</td>
<td>413WXXX57/54</td>
<td>413WXXX57 (Bronze PM)</td>
<td>413WXXX55 (Nylon)</td>
<td>Needle Bearing</td>
</tr>
<tr>
<td>Clutch</td>
<td>419WXXX54</td>
<td>419WXXX54</td>
<td>419WXXX54</td>
<td>419WXXX54</td>
</tr>
<tr>
<td>Sprocket</td>
<td>417WXXX57</td>
<td>417WXXX57</td>
<td>417WXXX57</td>
<td>Bearing Retainer</td>
</tr>
<tr>
<td>Spur Gear</td>
<td>407WXXX54</td>
<td>407WXXX54</td>
<td>407WXXX54</td>
<td>405WXXX54</td>
</tr>
<tr>
<td>Pulley</td>
<td>419WXXX54</td>
<td>419WXXX54</td>
<td>419WXXX54</td>
<td>W/TAB</td>
</tr>
<tr>
<td>Lip-Oil Seal</td>
<td>435WXXX51</td>
<td>435WXXX51</td>
<td>435WXXX51</td>
<td>W/O TAB</td>
</tr>
</tbody>
</table>

Options: HELP, RETURN, EXIT
Figure #3.3.5 - Ball Bearing Component Menu [28]

BALL BEARINGS

MAKE 1 SELECTION IN EACH CATEGORY WITH A DB:

NOMINAL SHAFT DIA (MM)  | 6  | 8  | 10  
SNAP RING                 | WITH | WITHOUT |
GRADE                     | ABEC-1 | SUB ABEC-1 |

XEROX PART NO: 413W30654
Table of Mechanical Design Selection Screen Menu:

<table>
<thead>
<tr>
<th>Compression Spring Design</th>
<th>Extension Spring Design</th>
<th>Pulley Belt Design</th>
<th>Gear Design</th>
</tr>
</thead>
<tbody>
<tr>
<td>Torsion Spring Design</td>
<td>Beam Design</td>
<td>Cam Design</td>
<td>Material Selection</td>
</tr>
<tr>
<td>Shaft Design</td>
<td></td>
<td></td>
<td>Exit</td>
</tr>
</tbody>
</table>
Figure #3.3.7 - Compression Spring Design Menu [28]

COMPRESSION SPRING DESIGN

KEYIN TITLE: LOADING SPRING EXAMPLE

SELECT END TYPE

SQUARED CLOSED ENDS

CURRENT

LENGTH (MM) ENTER VIA KEYPAD LOAD (N)

SPRING RATE (N/MM) STRESS (N/MM²)

SELECT DESIGN PARAMETERS

INITIAL LOAD INITIAL LENGTH FINAL LOAD FINAL LENGTH SPRING RATE FREE LENGTH

OPTIONAL INPUT

WIRE TYPE

MAX ALLOWABLE WIRE POST-PLATED MUSIC STEEL

SOLID HEIGHT DIAMETER 08-0014 08-0042 10-0023

HELP EXEC RETURN EXIT

PRESSURE_SPRING_2.1.1084 SELECT BY DATA BUTTON
Figure #3.3.8 - Compression Spring Output Example [28]

LOADING SPRING EXAMPLE

MANDATORY SPECIFICATIONS AND RECOMMENDED TOLERANCES

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Tolerance</th>
</tr>
</thead>
<tbody>
<tr>
<td>INSIDE DIAMETER (MM)</td>
<td>7.00</td>
<td>+ or - 0.13</td>
</tr>
<tr>
<td>WIRE DIAMETER (MM)</td>
<td>1.00</td>
<td>+ or - 0.035</td>
</tr>
<tr>
<td>FINAL LOAD (N)</td>
<td>13.3</td>
<td>+ or - 10%</td>
</tr>
<tr>
<td>FINAL LENGTH (MM)</td>
<td>12.7</td>
<td>BASIC</td>
</tr>
<tr>
<td>SPRING RATE (N/MM)</td>
<td>2.63</td>
<td>+ or - 10%</td>
</tr>
</tbody>
</table>

BETWEEN 11.1 AND 16.1 MM. FOR SQUARED (CLOSED) ENDS

MATERIAL - STAINLESS STEEL WIRE - XEROX SPEC 10-0023

SUGGESTED (REF) SPECIFICATIONS

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>OUTSIDE DIAMETER (MM)</td>
<td>9.00</td>
</tr>
<tr>
<td>MEAN COIL DIAMETER (MM)</td>
<td>8.00</td>
</tr>
<tr>
<td>NUMBER OF ACTIVE COILS</td>
<td>6.41</td>
</tr>
<tr>
<td>TOTAL NUMBER OF COILS</td>
<td>8.41</td>
</tr>
<tr>
<td>SPRING INDEX</td>
<td>8.00</td>
</tr>
<tr>
<td>PITCH (MM PER ACTIVE COIL)</td>
<td>2.30</td>
</tr>
<tr>
<td>FREE LENGTH (MM)</td>
<td>17.8</td>
</tr>
<tr>
<td>CALCULATED SOLID HEIGHT (MM)</td>
<td>9.41</td>
</tr>
<tr>
<td>MAX SOLID HEIGHT, IF SPECIFIED AS A MANDATORY PARAMETER, SHOULD NOT BE LESS THAN 9.68 BECAUSE OF TOLERANCE BUILDUP.</td>
<td></td>
</tr>
</tbody>
</table>

MAX STRESS ALLOWED FOR THIS WIRE 652. (APPROX 50,000 CYCLES)

STRESS AT FINAL LOAD (N/MM**2) 321.

STRESS AT SOLID HEIGHT (N/MM**2) 530.

*** EXAMINE XEROX DWG # 409W00471 & LEE SPRING # LC-035E-4SS FOR ABOVE SPRING. PARAMETERS FOR THE 409W00471 SPRING ARE:
*** D.O. = 9.10; WIRE DIA = 0.90; FREE LENGTH = 16.0; RATE = 2.70
*** USER SHOULD VERIFY NEW SPRING PARAMETERS BY RERUNNING PROGRAM.
Section III
Survey of Computer-Aided Design Techniques

Figure #3.3.9 - Gear Design Menu [28]

SPUR & HELICAL GEAR DESIGN

**KEY IN TITLE**
ISO PLASTIC GEAR PAIR EXAMPLE

<table>
<thead>
<tr>
<th>HELICAL ANGLE</th>
<th>PRESSURE ANGLE</th>
</tr>
</thead>
<tbody>
<tr>
<td>SPUR 0</td>
<td>14.5</td>
</tr>
<tr>
<td>HELICAL 12 - 25</td>
<td>20</td>
</tr>
<tr>
<td>25</td>
<td></td>
</tr>
</tbody>
</table>

**CENTER DISTANCE MM**

= 35.

**MATERIAL**

<table>
<thead>
<tr>
<th>MATERIAL</th>
<th>HOUSING</th>
<th>PINION</th>
<th>GEAR</th>
<th>LIFE CYC</th>
<th>MAX. TEMP</th>
<th>MAX. RPM</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.0008 ACETAL</td>
<td>*</td>
<td></td>
<td></td>
<td>1E4</td>
<td>65</td>
<td></td>
</tr>
<tr>
<td>0.0025 POLYCARBONATE</td>
<td></td>
<td></td>
<td></td>
<td>1E5</td>
<td>4</td>
<td></td>
</tr>
<tr>
<td>0.0012 POWDER METAL</td>
<td></td>
<td></td>
<td></td>
<td>1E6</td>
<td>5</td>
<td></td>
</tr>
<tr>
<td>NYLON 30% GLASS</td>
<td></td>
<td></td>
<td></td>
<td>1E8 UP</td>
<td>65</td>
<td>0.0017</td>
</tr>
</tbody>
</table>

**HELP EXEC RETURN EXIT**

**RETURN**
Figure #3.3.10 - Pulley Belt Design Menu [28]
IV. CASE STUDY OF COMPUTER-AIDED DESIGN TECHNIQUES

The case study which is presented in this chapter provides a user's perspective of the application of the more widely used CAE techniques available to the mechanical product design engineer. The basis of information for the sections which follow is derived from "hands on" experience which this author acquired at Xerox Corporation. The intent of this section is to develop a more complete understanding of how some of the techniques discussed previously in this paper are being implemented in commercial systems which are currently in use.

In order to carry out the case study, a benchmark part design was selected. Using this benchmark design as a common element, three commercial systems were used to investigate the various approaches for geometry creation and analysis. The three systems used for the case study consisted of Applicon, Intergraph, and PDA/Patran-G. The emphasis of the chapter will be to broadly describe the user interface techniques and capabilities that each of the systems provide in the mechanical product development process.
4.1 Benchmark Part Description

The benchmark part design selected for the case study is a clutch pawl from a drive control mechanism. It is constructed of standard acetal which is a low cost homogeneous thermoplastic material with mechanical properties well suited to the part application. A fully dimensioned manual drawing is shown in Figure #4.1.1 for reference. In addition, the material properties for this part are listed in Figure #4.1.2.

In order to adequately investigate the capabilities of the CAD systems, a requirement for the benchmark part was that it have a fair degree of 3-D complexity. This criterion would insure that, within the geometric modeling of the part, a wide range of system commands would be utilized. Another requirement of the part was that it be under an applied load in operation which could provide the basis for finite element stress analysis.
Figure #4.1.1 - Benchmark Part Detail Drawing [30]
### Figure #4.1.2 - Benchmark Part Material Property Table [31]

#### 1.0 DESCRIPTION

This selection guide covers selections and design data including usage guides, typical properties, and tolerancing information applicable to the included listing of standard Xerox Specifications for Acetal. The specifications listed in this Standard are for injection moldings, extrusions and fabricated parts.

#### 2.0 USES

See Plastic Materials MN3-30-010, Para. 4.3 (Tables 3A and 3B) and Para. 4.4 (Tables 4A and 4B) for Areas of Application.

#### 3.0 STANDARD TYPES AND REQUIRED PROPERTIES

<table>
<thead>
<tr>
<th>Type and Color</th>
<th>Xerox Spec. Number</th>
<th>Izod Impact Strength, min. (ft-lb/in)</th>
<th>Tensile Yield Strength, min. (psi)</th>
<th>Flexural Yield Strength, min. (psi)</th>
<th>Flexural Fatigue Strength, min. (psi)</th>
<th>Density (g/cm³)</th>
<th>Water Absorption max. (max%)</th>
<th>Deflection Temperature (°F)</th>
<th>Flammability U.L. Test</th>
</tr>
</thead>
<tbody>
<tr>
<td>General Purpose Injection and Extrusion Grade Unmodified Natural Color Black</td>
<td>30-0008 30-0009</td>
<td>0.64 (1.2) 56 (8,200) 83</td>
<td>1.40-1.45 (0.050-.052)</td>
<td>98 (208)</td>
<td>94HB</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>PTFE Modified Natural Color</td>
<td>30-0010</td>
<td>0.27 (0.5) 41 (6,000) 62.0</td>
<td>1.51-1.57 (0.054-.057)</td>
<td>13.7</td>
<td>94HB</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

* These properties are specified on Xerox Specifications
4.2 Applicon Graphics System
The Applicon 4000 series is a turnkey computer graphics system. The configuration used in the case study was installed at Xerox in 1983 with the intent of providing a turnkey system with complete 3-D computer-aided design / drafting capability and limited engineering analysis features. The 4245 version graphics processing facility used was based on the Digital Equipment PDP-11/34 processor. This system supports four Applicon 4650 Color Raster-Scan workstations and was running Applicon's 4750 3-D graphics application software.

4.2.1 Workstation Hardware Description
On the Applicon system the tabletizer terminal is the workstation at which the user performs design activities and manipulates system functions. Up to four tabletizers may be driven by the system. Each is an independent graphics input/output (I/O) terminal. The user workstation is equipped with the following devices that replace the traditional drawing board, paper, and drawing instruments:

- Graphics Display (CRT)
- Tablet and Pen
- Alphanumeric Keyboard
- Function Keyboard

The tablet, pen, and keyboards are input devices because the operator uses them to enter system commands. Figure #4.2.1 illustrates the layout of the Applicon workstation.
Figure #4.2.1 - Applicon Workstation [32]
The graphics display contains a Cathode Ray Tube (CRT) that displays the image of the drawing and drawing related information. The optional Color Raster Scan type CRT was utilized in this case study. The screen displays the user's drawing, data entries, system status, errors, and verification messages.

The tablet and electronic pen, or stylus, are used to enter hand drawn symbols when creating a drawing. The Applicon system has a unique built-in pen symbol recognition feature to interpret pen drawn symbols as commands. The pen is also used to activate menu commands from tablet assigned menus.

The alphanumeric keyboard, which resembles a typewriter keyboard, is shown in Figure #4.2.2. It is basically used to enter text, numeric data, and special characters.

The optional function keyboard is shown in Figure #4.2.3. It is an array of 64 micro switches in an 8 x 8 matrix. Each key represents a function that corresponds to a menu layout that the operator places over the micro switches. By pressing a function key, also called a function button, the operator activates specific system commands.

4.2.2 User Interface Fundamentals

The commands that the user enters into the system specify the operation(s) that the user wishes to have performed. These commands may be entered or deleted by means of the tablet and stylus, the alphanumeric keyboard, and/or the function keyboard.
Figure #4.2.2 - Applicon Alphanumeric Keyboard [32]
Figure #4.2.3 - Applicon Function Keyboard [32]
Section IV    Case Study of Computer-Aided Design Techniques

The tablet and pen offer the most convenient method of entering commands because it can recognize hand drawn symbols as the equivalent of long, complicated, typed commands. Imbedded in the surface of the tablet is a grid of intersecting wires that form a series of X, Y coordinates. When the user draws a symbol with the pen, the tablet can sense the location and direction of the user's strokes.

The tablet can also serve as a function keyboard by using a tablet menu. A user-defined menu is placed on the tablet to divide the surface into any number of segments. Each segment is called a Tablet Menu Command and is activated (or pushed) with the pen. Commands which are assigned to the individual segments can be executed by activating them with the pen in the specific area. A copy of the tablet menu used in the case study is shown in Figure #4.2.4 and will be discussed further in terms of command applications in a later section.

One of the unique aspects of the Applicon system is in the added functionality of the pen. The tip of the electronic pen contains a spring loaded switch that enters the pen position as data. The pen has three operating modes relative to the tablet which are illustrated in Figure #4.2.5.
Figure #4.2.4 - Applicon Table Menu [32]
Figure #4.2.5 - Applicon Electronic Pen Operation [32]
In the "Off" mode the position of the pen is more than 0.25 inches away from the tablet surface. On the graphics display, the small X-shaped cursor that follows the moving pen on the tablet stops moving. In the "Tracking" mode the tip of the pen is either touching the tablet surface without downward pressure, or is very near the tablet. The cursor on the display follows the pen to indicate the pen position relative to the screen. In the "Inking" mode, the user applies a light downward pressure on the pen, which leaves a faint tracing line on the screen as the cursor follows the movement of the pen. The system interprets this as a user input and processes the input. Inking the pen with no linear motion is called dotting. Figure #4.2.6 is an example of the possible commands which can be executed through this process. The actual application of this technique will be discussed further in the sections which follow.

The alphanumeric keyboard can also be used to enter any command. If the command applies to the control and manipulation of a graphics component, the operator must also type in the arguments for that command relating to the X, Y, Z coordinates. For example, the keyboard input "MOVE 2 -4 1;" can be used to move a selected component 2 units in the X direction, -4 units in the Y direction, and 1 unit in the Z direction. Due to convenience, though the user can enter any drawing command through the keyboard. This device is used mainly to type in text, arguments required for menu commands, and commands that are not defined by a tablet symbol.
Figure #4.2.6 - Applicon Pen Symbol Commands [32]

<table>
<thead>
<tr>
<th>Command 1</th>
<th>Command 2</th>
<th>Command 3</th>
<th>Command 4</th>
<th>Command 5</th>
<th>Command 6</th>
<th>Command 7</th>
<th>Command 8</th>
</tr>
</thead>
<tbody>
<tr>
<td>UNSA</td>
<td>GOSH</td>
<td>CVUE</td>
<td>VMOR</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>OR</td>
<td>OR</td>
<td>OR</td>
<td>OR</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>UNSV</td>
<td>UNSV</td>
<td>UNSV</td>
<td>UNSV</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>ADD</td>
<td>ADD</td>
<td>ADD</td>
<td>ADD</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>ADDA</td>
<td>ADDA</td>
<td>ADDA</td>
<td>ADDA</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>TAN</td>
<td>TAN</td>
<td>TAN</td>
<td>TAN</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>DELS</td>
<td>DELS</td>
<td>DELS</td>
<td>DELS</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>NAME</td>
<td>NAME</td>
<td>NAME</td>
<td>NAME</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>XYZ</td>
<td>XYZ</td>
<td>XYZ</td>
<td>XYZ</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>ADD TEXT</td>
<td>ADD TEXT</td>
<td>ADD TEXT</td>
<td>ADD TEXT</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>DADD</td>
<td>DADD</td>
<td>DADD</td>
<td>DADD</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Notes</td>
<td>Notes</td>
<td>Notes</td>
<td>Notes</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Section IV  Case Study of Computer-Aided Design Techniques
The function keyboard holds user-specified command menu layouts. It is an optional input device often used with the tablet and alphanumeric keyboard. Function keyboard menus expedite command input by providing the user with a means by which to string commonly used command chains into a single executable user command.

4.2.3 Geometry Creation

The first step in the case study on Applicon's Interactive Computer Graphics system involved the geometry creation of the benchmark part design. Based on the system capabilities, a 3-D wire frame modeling technique was utilized.

The creation of 3-D wire frame geometry, with even the moderate complexity of the clutch pawl, provided some challenges relative to visualization due to the transparent nature of these models. To aid in the visualization of the part geometry being created, or of neighboring parts being referenced, the system provides a variety of user-selectable options. The most significant of these view window manipulations is drawing level assignment and graphics element color assignment. The view commands, for example, let the user zoom in and out, rotate, or split the screen into four separate views. Drawing level assignment provides the flexibility to separate the part geometry into as many as 16 different levels which can be selectively turned on (visible) and made editable by the operator. Color assignment of the geometry being created can be made in any of 7 colors to also assist in visually separating sections of the part geometry as it is being viewed on the color display.
In the command sequences which follow, the inputs are bolded in quotations and are followed by the method of input and a short description of the operation. Tablet menu commands reference their location in parenthesis as they are shown in Figure #4.2.4. Likewise, pen symbol commands are referenced to their location in Figure #4.2.6. The procedure to input these various commands is highlighted in the User Interface section.

To initiate the drawing it is convenient to create a reference point at the origin (0,0,0) of the part which is also centered within the 16,777 cubic millimeter drawing volume of the system. Therefore, the following command sequence can be inputted to place a point at the center of the system’s drawing volume. These initial commands are made with the view set as a front view centered at the origin.

1.0 Add a point at origin to provide 0,0,0 reference

1.1 "Set Vector 1 at 0,0,0"

- Tablet menu command (1, 22)
- Set Vector 1 at drawing volume origin

1.2 "Add Point at V1"

- Tablet menu command (22, 24)
- Point element added at location of Vector 1

1.3 "GOSH"

- Pen symbol command (1, 12)
- Go Show to execute prior commands and display changes on the screen
A cross would now appear on the display to indicate the location of the point which has been created at the origin. Next, a circle will be added to represent the inside diameter on the back face of the clutch pawl pivot point.

2.0 Add a circle centered at the origin
2.1 "SELV"
   - Pen symbol command (1, 11)
   - Select Vertex by inking pen symbol over origin point
2.2 "GOSH"
   - Pen symbol command (3, 12)
   - Go Show to execute step 2.1 and display selected vertex as indicated by a butterfly symbol placed by the system at the origin point
2.3 "DIA @ S?"
   - Tablet menu command (1, 18)
   - Initiates add circle command with user defined diameter centered at selected vertex
2.4 "3.60 (EOC)"
   - Alphanumeric key in
   - Define nominal diameter and signals end of command (EOC)
2.5 "GO"
   - Pen symbol command (2, 12)
   - Go executes previous commands and repaints entire screen
The display would erase completely and repaint (redisplay) with the previously created point and newly added circle of diameter 3.6 units centered at that point. Next, this circle can be copied to the front face of the clutch pawl.

3.0 Copy the circle to the front face

3.1 "SELC"
- Pen symbol command (3, 11)
- Select center by inking pen symbol over the entire circle to completely select the element

3.2 "UNSV"
- Pen symbol command (8, 11)
- Unselect origin point by inking pen symbol over origin point only

3.3 "GOSH"
- Pen symbol command (3, 12)
- Go Show to execute steps 3.1, 3.2 and confirm selections
- Circle selection (presence of butterfly), and point unselection (absence of butterfly)

3.4 "COPY X, Y, Z"
- Tablet menu command (11, 18)
- Initiate copy command of selected element at user specified offset from original elements

3.5 "0 0 8 (RET)"
- Alphanumeric key in
Case Study of Computer-Aided Design Techniques

- Inputs X Y Z offset for copy command and carriage return (RET) key executes Go to erase and repaint screen

The resulting image on the display appears the same as it did prior to step 3 because the circle was copied 8 units in the Z direction and perfectly overlaps the original circle in a front view. The view could be changed to an isometric view to confirm the existence of the second circle.

4.0 Change view in the display to an isometric view

4.1 "SHOW ISO"
- Tablet menu command (13, 10)
- Initiates Show Isometric View command

4.2 "GO"
- Pen symbol command (2, 12)
- Executes step 4.1 and repaints the screen

The three elements created in this illustration would now be visible. Though this demonstrates only a small part of the geometry creation process, it does indicate the methodology for geometry creation on the Applicon Interactive Graphics Station. Figure #4.2.7 shows a hardcopy of the completed 3-D wire frame model representation of the clutch pawl design. The screen was set in a split mode to show orthogonal top, left, front, and right views.

If a detailed drawing of the clutch pawl was required, a drafting detailer would utilize a copy of the 3-D wire frame model to create this drawing. The
Figure #4.2.7 - Applicon Clutch Pawl 3-D Wireframe Model
process that the detailer uses starts by laying out the views required to adequately detail the part in a single view. This is accomplished through a combination of copy and rotate commands. Once the proper views have been established, the Applicon system provides a "smash" command to project the 3-D geometry onto a single 2-D plane and break all elements at the intercept points of overlapping lines and/or arcs. Next, the hidden lines are manually selected and deleted or changed to phantom lines. This labor-intensive process is symptomatic of the inherent limitations of 3-D wire frame models (as previously discussed in Section 3.2.1). Using this process in the case study, a hidden line isometric view of the clutch pawl was constructed and is shown in Figure #4.2.8.

The final step in creating the detail drawing involves the dimensioning process. Because the 3-D model is an accurate part representation, the transformed 2-D model will also be an accurate representation of the nominal part. Therefore, the automated dimensioning commands will simply measure the quantities specified by the detailer and create the appropriate dimensioning symbology. In the majority of the detail drawing creation, the draftsman need only insert the tolerances and drawing notes. Since the emphasis of this paper is centered on the tasks of a mechanical product design engineer, it will suffice to reference the tablet menu commands in Rows 1 to 16 and Columns 1 to 8 of Figure #4.2.4 as an illustration of table commands which support the automated drafting process. In addition to the tablet menu, the function keyboard menu is also commonly used to assign customized drafting commands and symbols in order to minimize detail creation time.
Figure #4.2.8 - Applicon Clutch Pawl Constructed Hidden Line View
4.2.4 Mechanical Properties Analysis

The Applicon system, on which this case study was conducted, had very limited capability beyond the 3-D wire frame geometry modeling and automated drafting capability. Experimental software was provided on the system in order to aid the design engineer in estimating mechanical properties relating the part volume and weight.

Prior to being able to apply this analysis program on the clutch pawl, the 3-D wire frame model created in the prior section had to be modified. To meet the requirements of the software, a set of closed boundaries had to be established, which, when projected over a user defined thickness, would approximate the part volume. A user command was provided to identify holes which had to be subtracted from the projections. These closed boundaries created from the original model are shown in an isometric view in Figure #4.2.9.

To perform the analysis, each boundary is individually selected and then estimated by keying in the command "OI 123" and responding to the system prompts for the type of analysis desired, accuracy, type of solid approximation, section thickness, and material density. The system then calculates the weight and volume and displays the results. The output from clutch pawl model analysis is shown in Appendix I. As a quick check of the analysis output, a prototype of the clutch pawl was weighed and compared to the sum of the estimated individual projection weights. The actual prototype pawl weight was 6.12 grams, compared to the model analysis estimate of 6.05 grams.
Figure #4.2.9 - Applicon Clutch Pawl Mass Properties Elements
4.3 Intergraph CAD System

The Intergraph Interactive Computer Graphics System is a complete stand-alone turnkey system. The configuration used in the case study was installed at Xerox in 1985, with the intent of performing 3-D design/drafting and more advanced computer-aided design analyses. The Intergraph system utilized was a version based on a Digital Equipment VAX 11/751 Processor. This system supports sixteen "Interact" color production model workstations and is programmed to run Intergraph's Interactive Graphics Design and Mechanical Design and Drafting System Software.

4.3.1 Workstation Hardware Description

The Intergraph System, much like the Applicon System discussed in Section 4.2, uses a design/digitizing station for user interface. At this workstation the operator can perform all drafting and design activities and control system functions. The Intergraph system used in the case study would support up to 16 independent graphics input/output (I/O) terminals. Though various workstation options are available from Intergraph, this case study was confined to the full function color "Interact" configuration.

The Interact workstation is equipped with the following devices to support the users in performing various CAD activities in product design:

- Dual screen graphics display (CRT)
- Digitizer table and cursor pad
- Alphanumeric keyboard
The digitizer table, cursor, and alphanumeric keyboard are the input devices that the operator uses to enter system commands. Figure #4.3.1 illustrates the layout of the Intergraph "Interact" workstation.

The dual screen graphics display contains two separate cathode ray tubes (CRT's) that display the image of the drawing and drawing-related information. The configuration used in the case study consisted of the Optional Color Raster Scan type CRT on the right display and a monochromatic CRT on the left. The unique dual screen capability of the Intergraph workstation allows the user to define various combinations for the display of the drawing graphics, data entries, system status, errors, and command prompts.

The digitizer table and cursor pad are used to accomplish a number of input functions. One of the most frequently used functions is to activate menu commands from digitizer table assigned menus. By moving the cursor pad on the digitizer table, the operator can also move the visual cursor on the graphics screens in order to identify elements or locations. The cursor pad contains twelve integral buttons which are used in combination with cursor table locations or visual cursor screen locations to execute the various input commands.

The alphanumeric keyboard provided with the Intergraph workstation resembles a standard typewriter keyboard with some enhancements. These enhancements include fourteen function keys, various display control keys,
Figure #4.3.1 - Intergraph Workstation [33]
and an additional numeric keyboard. Figure #4.3.2 shows the layout of this keyboard.

4.3.2 User Interface Description

The user inputs commands to the system on the Intergraph workstation through a variety of techniques in order to specify the operations the user wishes to have performed. These commands are entered interactively by means of the digitizer table, cursor pad, and/or the alphanumerical keyboard.

Similar to the Applicon system, the digitizer table and cursor pad provide the most convenient method of entering commands. As the cursor pad is moved to different locations on the digitizer table, the position of the crosshairs on the pad window is accurately measured relative to the X and Y coordinates on the table. This information is also used to move the visual cursor on the CRT displays. The operator inputs the desired information into the system by depressing the appropriate cursor button when the position has been identified. Figure #4.3.3 illustrates the Intergraph cursor pad layout along with a description of the four commonly used menu buttons to execute commands (C), input data (D), reset or reject data (R), and locate tentative points (T).

The primary function of the command button on the cursor pad is to enter commands from a defined table menu. A user-defined table menu is placed on the digitizer table to divide the surface into any number of segments. The user initiates a command specified in a segment by aligning the cross hair
Section IV  
Case Study of Computer-Aided Design Techniques

Figure #4.3.2 - Intergraph Alphanumeric Keyboard [33]
Figure #4.3.3 - Intergraph Cursor Pad [33]

AND BUTTON
The command button is used to select commands from the command menu. This is accomplished by placing the crosshair of the cursor over the desired command and pressing the 'C' button on the cursor. You will see the active command displayed in the header.

A BUTTON
The data button is used to input \((x, y)\) points to the system. To enter a data point by the cursor, move the cursor until the tracking symbol (visual cursor) is located at the correct screen location and press the 'O' button on the cursor.

ET/REJECT BUTTON
The reset/reject button is used to clear out any input points and leave the user in the current command mode. As a reject button, it will reject elements after they have been identified for manipulation by the data button.

TENTATIVE POINT BUTTON
The tentative point button is used to locate points \((x, y)\) within the design plane. This is done by placing the visual cursor at the desired location on the screen and pressing the 'T' button on the cursor. You will see the \(x, y\) coordinates displayed in the header at the bottom of the screen.
window on that segment and depressing the command button on the cursor pad. A sample of the mechanical design table menu used in the case study is shown in Figure #4.3.4.

In contrast, the data and tentative buttons on the cursor pad are used primarily in conjunction with the position of the visual cursor tracking symbol on the screen. The operator would locate the tracking symbol on the desired location to be entered, or the element to be selected, on either screen. Depressing the tentative button will cause the system to respond with the coordinates of the tracking symbol location it is recognizing and/or highlight the element being identified. The data button could then be depressed to accept and input that information to the system. The reject button, if depressed, would typically be used to reject an incorrect selection and allow reselection, or exit the command. The remainder of the buttons on the cursor pad are used in more specialized commands and intricate 3-D data input.

The alphanumeric keyboard is used by the operator most frequently to input arguments for commands. In these cases, the keyboard provides the user with a convenient means of entering precise data to the system. For example, in executing a circle creation command, the diameter could be inputted by keying in the exact value or using a cursor location data entry command. The fourteen function keys on the keyboard also provide the capability for frequently used commands to be assigned by the user to minimize typing. These function keys could be compared to the optional function keyboard on
Figure #4.3.4 - Intergraph Mechanical Design Command Menu [33]
the Applicon system. More detailed applications of the user interface on the Intergraph workstation will be discussed in the sections which follow.

4.3.3 Geometry Creation

The case study using the Intergraph system was addressed in a manner consistent with that of the Applicon equipment. In addition to the 3-D wire frame modeling, this system also had surface modeling capability. Because of the high degree of similarity in the overall creation techniques between the two systems, more emphasis will be placed on the discussion of the surface modeling techniques.

Whether one is working with 3-D wire frame or surface models, there is still a visualization challenge for the designer creating the geometry. The Intergraph system, like Applicon, also provides a number of features to help minimize this problem. One significant hardware enhancement using the Interact workstation is the second display screen. This feature allows up to 8 operator specified views to be shown simultaneously, 4 on each display. In the generation of complex 3-D geometry this additional viewing capability is very helpful in terms of enabling the user to work in various views at different viewing angles at the same time, while keeping the overall part geometry visible.

System software on Intergraph helps in the visualization of the geometry by providing a rich assortment of view window options, element symbology, level
assignment, and reference file options. Beyond the basic view commands discussed previously, the Intergraph system provides some advanced dynamic view commands which allow the operator to progressively rotate and pan in or out on the graphics on the screen. The user selectable geometry descriptors are lumped into what is referred to as element symbology. Element symbology defines the color, weight (width), and code (style) of the element. The system provides 32 different line weights (increasing in width from 0 to 31), 32 different colors, and 8 different styles (i.e., solid, dash, and dot combinations). Intergraph also supports 63 drawing levels which can be turned on or off, with one level designated as the active level for geometry creation or modification. Reference drawing files are another key visualization tool on this system. For example, this capability allows the user to simultaneously view on the screen a neighboring part being designed by another user to insure proper interface and/or clearance.

To input geometry on the Intergraph system, once in the design graphics mode, the operator interactively selects and executes commands using a combination of cursor pad and alpha numeric key-ins. To illustrate the process of surface geometry creation on the Intergraph system, the procedure to generate the same basic section of the clutch pawl as was demonstrated on the Applicon system is presented. One will observe, that although the end product is surface geometry, the creation technique involves the creation of wire frame elements as well.
The command sequence, which follows the inputs, are again shown in bolded quotations and are followed by the method of input, and a short description of the operation. The tablet menu commands listed refer to the basic mechanical design command menu which is shown in Figure #4.3.4. In addition, a specialized tablet matrix menu is introduced to provide the surface geometry creation commands. The mechanical design surface matrix menu is shown in Figure #4.3.5 and is utilized in a manner identical to the basic mechanical design tablet command menu as was highlighted in the User Interface section (4.3.2).

To initiate the geometry creation, a construction point at the origin (0,0,0) of the part should be added, which is also centered within the 429,496 cubic millimeter drawing volume of the Intergraph system. Therefore, the following command sequence can be inputed to place this point. This primary command sequence is made in a view set as a front view centered at the origin.

1.0 Add a point at origin to provide 0,0,0 reference

1.1 "Construct Point-Active Point"
   • Tablet menu command
   • Initiates construct active point command at user specified location

1.2 "XY = 0,0,0 (RET)"
   • Alphanumeric Key In
   • Defines location in drawing coordinates
Section IV Case Study of Computer-Aided Design Techniques

Figure #4.3.5 - Intergraph Design Surface Matrix Menu [33]
The display would now show a point at drawing location 0,0,0. Next, a circle will be added to be used to construct the inside diameter of the clutch pawl pivot point.

2.0 Add a circle centered at the origin
   2.1 "Place Circle Using Keyboard-Defined Diameter"
   - Tablet menu command
   - Initiates place circle command at user specified diameter and center location
2.2 "3.60 (RET)"
   - Alphanumeric Key In
   - Define nominal diameter
2.3 "Input Center"
   - Cursor pad command
   - Enter data identifying center of circle by aligning visual cursor on point constructed in step 1.0, then pressing tentative button (T) to light up point and attach cross-hair, and pressing data button (D) to enter data."

A circle will now appear on the screen with a diameter of 3.6 units centered at the origin. Next, this circle can be used to construct a cylindrical surface to represent the inside diameter of the clutch pawl pivot.

3.0 Create cylindrical surface for pivot inside diameter
Section IV  Case Study of Computer-Aided Design Techniques

3.1 "Construct Right Circular Cylinder"
- Surface matrix menu tablet command
- Initiate construct right circular cylinder command using existing circle and user specified height

3.2 "Identify Boundary Circle"
- Cursor pad command
- Enter data identifying boundary circle by aligning visual cursor on circle constructed in step 2.0, then pressing tentative button to verify selection, and pressing data button to enter data

3.3 "DL = 0, 0, 8 (RET)"
- Alphanumeric Key In
- Enter height on cylinder as 8 mm in Z direction

Due to the viewing angle on the display being a front view, the geometry appears as one circle which is centered about the point. The view can be changed to an isometric one in order to confirm the existence of the cylinder which was created.

4.0 Change view in the display to an isometric view
4.1 "Isometric View Selection"
- Tablet menu command
- Initiate command to orient user selected view as isometric

4.2 "Identify Views"
- Cursor pad command
- Identify view with visual cursor in top right corner of view 1

The view will automatically update and show the isometric view of the wire frame representation for the right circular cylinder that we created.

The operator can continue to create the surface model geometry through similar modeling techniques as that used for the simple right circular cylinder. The other widely used commands supported by the system include tabulated cylinders, ruled surfaces, and surfaces of revolution. Though only a small segment of the clutch pawl geometry has been created by the above commands, one can develop a sense for the methodology for surface model geometry creation on the Intergraph Interactive Graphics System. Figure #4.3.6 shows a hardcopy of the completed 3-D surface model boundary representation of the clutch pawl design. This transparent boundary representation of the surface model is almost identical in appearance to a 3-D wire frame geometry model. In fact, the 3-D wire frame model was also created on the system and is shown in Figure #4.3.7 for reference. In order to take advantage of the visualization capability of the surface model, a hidden line plot can be run.
Figure #4.3.6 - Intergraph Clutch Pawl Transparent Surface Model
Figure #4.3.7 - Intergraph 3-D Wireframe Model
Therefore, to create a hidden line plot of the clutch pawl geometry, the operator inputs the following command sequence.

5.0 Create a hidden line plot of the cylinder
5.1 "Hidden Line Plot"
- Tablet menu command
- Requests hidden line plot screen menu
5.2 "Hidden Line Option Selection"
- Screen Menu command(s)
- Identify any changes in the default options for the hidden line plot to be created by placing visual cursor in desired selection on screen menu and depressing data button
5.3 "Execute Hidden Line Plot"
- Screen Menu Command
- Initiate execution of hidden line plot by placing visual cursor in execute block of hidden line plot screen menu and depressing data button

The hidden line screen menu used in these operations is shown in Figure #4.3.8. Once the hidden line plot is initiated the system will provide a series of prompts signaling that the computations are being made and then the screen will be updated to illustrate the hidden line plot which was requested. Three variations of hidden line options are available on the system. These include a hidden line plot with no mesh, hidden line plot with mesh, and a color shaded hidden line plot. These plot options are illustrated for an
isometric view of the clutch pawl in Figures #4.3.9, #4.3.10, and #4.3.11, respectively.

One can quickly realize that there is a significant visualization benefit in surface geometry models. Though this is certainly the case, there are limitations to these benefits. For instance, hidden line plot execution represent only a temporary snapshot on the Intergraph system. Once geometry creation is resumed the operator has to work again in the transparent surface boundary mode. It is also important to note that the solid appearance of the hidden line plots is only a shell. That is, these surfaces have zero thickness, occupy zero volume, and have no mass properties.

The detail drawing creation process from the surface model geometry is very similar that which was discussed for the Applicon system using 3-D wire frame geometry. Intergraph similarly provides commands to project the geometry onto a single plane and add the necessary detail drawing delineation. The mechanical design automatic dimensioning menu, which is used in this task, is shown in Figure #4.3.12.
Figure #4.3.8 - Intergraph Hidden Line Scene Menu [33]
Figure #4.3.9 - Intergraph Clutch Pawl Hidden Line Plot - No Mesh
Figure #4.3.10 - Intergraph Clutch Pawl Hidden Line Plot - Mesh
Figure #4.3.11 - Intergraph Clutch Pawl - Color Shaded Image
### Section IV  Case Study of Computer-Aided Design Techniques

**Figure #4.3.12** - Intergraph Dimensioning Matrix Menu [33]

#### INTERGRAPH
MECHANICAL DESIGN

<table>
<thead>
<tr>
<th>AUTOMATIC DIMENSIONING</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>PLACEMENT</strong></td>
<td><strong>JUSTIFICATION</strong></td>
</tr>
<tr>
<td>AUTO</td>
<td>L</td>
</tr>
<tr>
<td>MAN</td>
<td>C</td>
</tr>
<tr>
<td>ON</td>
<td>R</td>
</tr>
<tr>
<td>OFF</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th><strong>WITNESS LINES</strong></th>
<th><strong>UNITS</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td>AUTO</td>
<td>LENGTH</td>
</tr>
<tr>
<td>MAN</td>
<td>DEGREES</td>
</tr>
<tr>
<td>ON</td>
<td></td>
</tr>
<tr>
<td>OFF</td>
<td></td>
</tr>
</tbody>
</table>

**TEXT**

<table>
<thead>
<tr>
<th>PLACE</th>
<th>JUSTIFICATION</th>
</tr>
</thead>
<tbody>
<tr>
<td>VI</td>
<td>L</td>
</tr>
<tr>
<td>VI</td>
<td>C</td>
</tr>
<tr>
<td>VI</td>
<td>R</td>
</tr>
</tbody>
</table>

**FIT**

<table>
<thead>
<tr>
<th>COPY &amp; INCRE TEXT</th>
<th>L</th>
</tr>
</thead>
<tbody>
<tr>
<td>EDIT</td>
<td>C</td>
</tr>
<tr>
<td>HIGHT</td>
<td>R</td>
</tr>
<tr>
<td>WIDTH</td>
<td></td>
</tr>
</tbody>
</table>

**TEXT JUSTIFICATION**

<table>
<thead>
<tr>
<th>XX</th>
<th>XX</th>
<th>XX</th>
</tr>
</thead>
<tbody>
<tr>
<td>XX</td>
<td>XX</td>
<td>XX</td>
</tr>
<tr>
<td>XX</td>
<td>XX</td>
<td>XX</td>
</tr>
</tbody>
</table>

**TEXT FONT MODIFICATION**

**ENTER DATA**

<table>
<thead>
<tr>
<th>FILL IN SING</th>
<th>JUSTIFY</th>
</tr>
</thead>
<tbody>
<tr>
<td>AUTO</td>
<td>L</td>
</tr>
</tbody>
</table>

**ANNOTATION**

**TEXT NODES**

<table>
<thead>
<tr>
<th>NODE</th>
<th>V I NODE</th>
<th>TEST MODE</th>
<th>DISPLAY MODE</th>
</tr>
</thead>
<tbody>
<tr>
<td>XX</td>
<td>XX</td>
<td>XX</td>
<td>XX</td>
</tr>
<tr>
<td>XX</td>
<td>XX</td>
<td>XX</td>
<td>XX</td>
</tr>
<tr>
<td>XX</td>
<td>XX</td>
<td>XX</td>
<td>XX</td>
</tr>
</tbody>
</table>

**COMPONENT CATALOG**

PLACE COMPONENT IDENTIFICATION TAG

PLACE PARTS REPORT

*MDDS 86J 5/1/83 AM-MECH*
4.3.4 Mechanical Properties Analysis

The Intergraph system provides a number of commands to support both sectional and mass properties analyses. Considering that we have created the surface model representation of the clutch pawl benchmark design discussed in the previous section, the application of these computer-aided design techniques is fairly simple. This process is less complicated when using the surface model because the operator has to provide less information to the system to complete the calculations. In fact, calculation of the sectional properties of any surface can be made by initiating the appropriate tablet command and identifying the surface element in which the properties are desired. The system will automatically calculate the area, perimeter, centroid, principal axes, and principal moments of inertia. The results are then displayed in the form of a graphic cell of the screen. Again, the Intergraph system utilizes a matrix menu to help the operator complete this task. The matrix menu with these commands is shown in Figure #4.3.13.

In this specific case study the mass properties of the clutch pawl were examined. To enable the system to make these calculations, implied volumes have to be established. These volumes can be defined through projection or revolution of user specified surfaces. Therefore, in the case of the clutch pawl, the user can select the individual surfaces which can be used to create implied volumes that in total would approximate the true clutch pawl. In order to prepare for this analysis, the user might determine this subset of surface elements from the total surface model and copy each one onto a unique drawing level. Then the user could systematically address each element by
Figure #4.3.13 - Intergraph Mechanical Properties Matrix Menu [33]
level, with all other levels turned off in that view, and then calculate the mass properties for each one. Upon completion of the individual implied volume calculations, a composite volume can be formed.

For example, in the case of center cylindrical shape of the clutch pawl, the user would initiate the "Mass Properties of Projection" tablet menu command. The system would then prompt the user to input material density, identify the element to be projected, identify any holes in the element, and locate the projection point. The system would then carry out the projection and calculate the volume, mass, mass center, and principal moments of inertia. The results of these calculations are then displayed in the form of a graphic cell with its origin at the mass center and its orientation corresponding to the principal axes.

Once all the individual implied volumes, like the center cylinder, have been approximated, the composite "payload computation" tablet command is utilized. With all individual element viewing levels on, the user identifies the graphic cells to be integrated as a composite and the system will place a new cell for the entire clutch pawl volume. The output from this analysis is shown in Appendix II. The results of the analysis output of the pawl weight is 6.03 grams, as compared to the actual prototype weight of 6.12 grams and the Applicon system output of 6.05 grams.
4.4 PDA/Patran-G System

Patran-G is advertised as a general purpose interactive graphics pre- and post-processor for the construction, display, and editing of three-dimensional finite element models. Unlike the Applicon and Intergraph systems discussed in the previous sections, Patran-G is a software system which is licensed by PDA Engineering to run on a firm's existing computer system and various graphics terminals. The case study application was conducted using a Digital Equipment VAX 11/780 super mini-computer with a Tektronix 4109 color graphics terminal. Due to differences in the features and the capabilities of each processor and interface terminal, the descriptions contained in the case study application may vary from those on a different system. In addition, it is important to note that this case study was completed using Release 1.5 of Patran-G and may be subject to change as the software is enhanced in future releases.

4.4.1 Workstation Hardware Description

The terminal used for the interactive computer graphics within the Patran-G case study was much less sophisticated than the Applicon and Intergraph workstations. The Tektronics 4109 is a basic color CRT terminal. This terminal has a conventional alphanumeric keyboard with the addition of thumb wheels for vertical and horizontal on-screen cursor control.

4.4.2 User Interface Fundamentals

Within the Patran-G environment, data is presented on the screen in both graphical and textual form. The bottom of the screen is called the "alpha screen" and it is through this region that all computer and user requests and
responses are presented. The remainder of the screen is dedicated to graphics.

Patran-G makes use of the alpha screen for user interface through what is referred to as "dynamic menus". These dynamic menus provide a list of options which are commonly used at a given point in the execution. These menus, and their respective options, change as the user progresses through the modeling process. The hierarchy for these menus is shown in Figure #4.4.1. The user simply inputs the number which corresponds to the desired option on the menu and then responds with the appropriate alphanumeric and/or cursor directive.

To control the position of the screen cursor on the Tektronix terminal, there are two thumb wheel controls, one for vertical movement and one for horizontal movement. An alternate means of cursor control is also provided through the use of the keyboard. A compass correspondence is established centering around the "K" key, which define direction and magnitude of cursor movement when prompted by the system. Figure #4.4.2 illustrates this cursor control keyboard convention. This more cumbersome means of cursor control is representative of some of the efficiency which is lost using a less sophisticated terminal as compared to the Applicon or Intergraph workstations.

In general the basic terminal approach for user interface in the Patran-G case study consists of predominantly alphanumeric key-ins and requires a significant amount of familiarity with the available command options and the
Figure #4.4.1 - Patran-G Menu Hierarchy [34]
Figure #4.4.2 - Patran-G Keyboard Cursor Control Diagram [34]
specific format required for their input. An example of a simple command to create a point, called a grid point, would be typed in as "GRID, 1, , 3/7/5." The system would then respond by placing a grid point, with label #1, at the coordinates of 3 in the X, 7 in the Y, and 5 in the Z. In the sections which follow, a more detailed look at the command structure and applications are discussed.

4.4.3 Geometry Creation

Patran-G is based on a systematic approach towards analytical modeling. The first step in this approach, referred to as Phase I in Patran-G, is geometric modeling. This phase involves the creation of an accurate surface or solid model of the structure. In this case study, the solid modeling approach will be utilized.

Similar to the Appicon and Intergraph systems discussed previously, Patran-G provides various options for the user to control graphical data presentation. Some of the more commonly used options include multiple screens, view angle, window size, active set, and color assignment. The system is capable of displaying up to 16 screens simultaneously, though in most applications, viewing more than 4 is not practical due to the size of the CRT. Viewing angle commands permit the operator to select and modify the angular orientation of the graphics, while window commands provide zoom in and out functions. Active set commands allow the user to view any subset of the total data base in order to minimize view complexity. Additionally, Patran-G supports up to 16 colors which can be assigned to various elements by the user.
In general, each of these graphics commands are initiated by an alphanumeric key-in and in some situations, the sequence can include visual cursor input. For example, a screen window can be modified by selecting the "window" option in the display menu. The window menu would then appear and the user could select the "corners" option. Next, the system would prompt the user to input cursor locations for the bottom left corner and upper right corner of the desired window. Then, the user keys-in a "plot" command to erase screen and replot with the new window.

To begin the geometry creation phase, the user would select the geometry creation option from the mode menu. At this point, a key-in approach can be initiated to begin the clutch pawl part model construction. Since earlier discussions in this case study have explored surface geometry using the Intergraph system, this section will focus on the solid modeling technique.

Patran-G utilizes a boundary representation technique in creating solid geometry. This approach typically begins with definition of points called a "grid point". These grid points are then used to create parametric cubic functions which can simply be referred to as a "line". Continuing on, the operator uses the lines to construct a surface geometry elements called a "patch". Finally, the patch surface can be used to construct solid geometry elements referred to as a "hyperpatch". During all Phase I Geometry Creation, a common construction directive format is used for all alphanumeric key-ins which is referred to as the "NOODL" rule:
Name of item, output list, option, data, list 1, list 2, list 3

The first field called "name of item" refers to the type of Phase I geometry being created, like a line. Next, an "output list" is looking for the number to be assigned to the element being created. If the user has no preference, a "#" symbol can be placed in this field and the system will select the next available number. The "option" field is requesting the user to identify which of a multitude of construction options is being utilized in this directive. Examples of options include "tran" for translation or "rot" for rotation. The remaining "data" and "list" fields are used to input data required for the option like "X/Y/Z" cartesian coordinates, or list of element numbers like "1 to 8" meaning grid points 1 through 8.

An example of a Phase I Geometry Directive, which constructs a hyperpatch with label 2 from existing exterior patches labeled 1 through 6, is the use of the hyperpatch "face" option keyed-in as "HP, 2, FA, 1T6". A solid cube would then be created and automatically added to the active screens.

Similar to the surface model created on Intergraph, the solid models created with Patran-G appear as transparent boundaries representations. Figure #4.4.3 shows the completed solid model of the clutch pawl in this format. Upon review of this model, one can note that the structure is made up of a large number of hyperpatches. Though this number could have been
Figure #4.4.3 - Patran-G Transparent Solid Model
substantially reduced, and simplified in appearance, the finer detail will aid in the finite element model construction which will follow.

Various display options are available in Patran-G to support visualization of the model. These options include hidden line plots, shrink features, and color shaded images. Shrink is a capability that has not been discussed previously, but which plots an item smaller than it actually is to aid in visually separating the individual components of a model. The objects, in this case the hyperpatches, are shrunk toward their centroids by a user specified factor. Figure #4.4.4 shows a hidden line plot of the clutch pawl solid model with a 30% shrink factor applied. Patran-G provides the flexibility for the user to ignore the current menu options and make "unprompted requests" for set, show, or run operations like the previous plot. The user would key in a set command with a shrink factor of 30% for the Phase I geometry as "set, SH1, .30". Next, the hidden line plot would be requested by keying-in "run, hide". Color shaded images can also be produced by adding a qualifier to the hidden line plot request by keying-in "run, hide, solid". The color shaded image of the clutch pawl using this command is shown in Figure #4.4.5, as an isometric view. The X Y Z coordinate system is provided on the screen (and plots) at all times to assist the user in relating back to the fixed axes of the model.

Due to the fact that Patran-G is specifically intended as a finite element pre-processing and post-processing system, much of the geometric modeling techniques are geared toward that application. Therefore, Patran-G does not provide any type of detail drawing creation features. Limitations such as
Figure #4.4.4 - Patran-G Clutch Pawl Hidden Line Plot - 30% Shrink

Hidden Line Plot with 30% Shrink
Figure #4.4.5 - Patran-G Clutch Pawl Hidden Line Plot - Color Shaded
these, and possible alternatives for a product development group, will be addressed in the discussion section of this paper.

4.4.4 Finite Element Analysis

By utilizing the solid model geometry discussed in the previous section as a framework, the user can now construct a finite element model and analyze the clutch pawl under its applied load.

Patran-G continues its systems approach to this task by separating these next steps into three phases. Whereas Phase I was referred to as the Geometric Modeling Phase, Phase II is called the Analysis Modeling Phase. Following the construction of the finite element model, the actual analysis is done in Phase III. This analysis is done outside the Patran-G environment by a separate software package, MSC-NASTRAN in this case, and will only be discussed briefly. After analysis, the results are inputted back into Patran-G for Phase IV which involves interactive graphics post processing of the analysis results. Because of the complexity level involved in these phases, only an overview of each is presented in this section. A more detailed description of these steps can be found in Patran-G and MSC NASTRAN user guides which are referenced in the bibliography [34].

The creation of the analysis model in Phase II basically involves subdividing the geometry of the structure into defined finite elements, applying the external loads and constraints, and assigning physical properties to the
elements. Along the way in this process, Patran-G provides various tools to help check and optimize the model.

The first step of Phase II requires the user to subdivide the entire geometry model into "nodes". These node points represent coordinate locations at which finite elements will subsequently be connected. To accomplish this task in Patran-G, a "GFEG" directive is utilized with the general format "GFEG, geometry ID, node type, mesh". For example, the user would key-in "GFEG, H5, G, 8/10/4" to create grid nodes (G) from hyperpatch 5 (H5) in an 8-by-10-by-4 uniform mesh (8/10/4). It is important in this step to insure that the nodes of neighboring geometry elements, such as the hyperpatches in the clutch pawl, be oriented in such a way that connectivity is achievable. That is to say, that the nodes of two neighboring hyperpatches of a homogeneous structure will have to coincide. Though this characteristic will become more evident in the later steps, it was a driving factor in the creation of a more dense, but aligned, hyperpatch structure in Phase I. It is also important to consider higher node densities in expected high stress areas for better accuracy.

The next step in Phase II involves the creation of elements which connect the node points. This task utilizes a "CFEG" directive with the general format "CFEG, geometry ID, element type". A sample key-in of this type is "CFEG, H5, HEX" which creates standard 8-node hexahedra elements (HEX) within hyperpatch 5 (H5). The user would complete this process for the entire structure.
After the complete structure has been approximated with elements, some maintenance is required on the common boundaries of each geometric subdivision, or hyperpatch. The nodes which coexist at the same point need to be equivalenced. That is to say, the points will be given a single ID. Patran-G provides automatic equivalencing using either topological or geometric methods. This procedure is selected from the Phase II Analysis Model menu. As Patran-G performs the automatic equivalencing operation, a green circle is placed over equivalenced nodes to identify them in the active screen.

Once the model finite element structure has been equivalenced, the applied external loads and constraint data must be generated. The "DFEG" directive is used with general format "DFEG, geometry ID, option, data, set ID, include list, coordinate ID". An example of this command is "DFEG, H1O, FORC, 23/16, 500, N100" which applies a concentrated force (FORC) of 23 units in the X direction and 16 units in the Y direction (23/16) as part of load set 500 (500) to node 100 (N100). Similar commands can provide displacement constraints as well. These directives were used in the case study to apply a load and a constraint case to the clutch pawl which represents the maximum load case in operation. As these loads and constraints are applied, Patran-G provides visual feedback with force vectors and cyan circles for the displacement constraints.

To complete the finite element model, the user has to define the property attributes of the structure. Because the clutch pawl is a homogeneous body, a
single property record was entered and a property identification number was assigned to each of the elements in the model. This task is accomplished with a "PFEG" directive in Patran-G using the general format "PFEG, geometry ID, element type, data, property ID, include list". An example would be "PFEG, H1T#, HEX, 10" to assign property record ID number 10 (10) to the Hex elements (HEX) in all hyperpatches (1T#).

The final steps of Phase II Analysis Modeling involve editing of the model and model optimization. The case study clutch pawl required some editing to create spring attachment holes in the structure. To accomplish this modification, the edit feature allows the user to delete an element and to move node points to approximate the hole location and shape. Model Optimization is an automatic process in Patran-G which removes unreferenced nodes, compacts the node numbering sequence, resequences the node numbering to minimize bandwidth, and compacts the element numbering sequence. The optimization procedures are initiated from the Phase II Analysis Model menu.

After completing these steps, the clutch pawl finite element was complete and is shown in Figure #4.4.6. In this final form, the model consisted of 687 nodes and 311 elements. The load case, labeled subcase 1, is the maximum load of the pawl in operation, and subcase 2 is the clutch pawl under gravity effects.

In order to conduct Phase III, the actual analysis of the finite element, a neutral file has to be created. Patran-G leads the user through this process by
Figure #4.4.6 - Patran-G Clutch Pawl Finite Element Model
using the neutral output menu. The neutral file provides output from Patran-G in a form which can be easily used by an external program. In the case study, the neutral file was then operated on by a translation program called "PATNAS". This converts this neutral file data into a bulk data deck for input to MSC/NASTRAN which is a commercial finite element analysis program. In a similar fashion, output from the completed NASTRAN analysis must then be translated back into a results neutral file for input to Patran-G. This output file goes through an inverse analysis translation program called "NASPAT" which creates the results files readable by Patran-G for displacements and nodal stresses for each subcase.

Once the results from the analysis have been translated, Phase IV post-processing can be initiated by the user. The final phase involves the graphical review and interpretation of the analysis results. Patran-G is designed to be a significant aid to productivity by helping the user visualize the behavior of their mathematical models. The two key methods used in this process include deformed geometry views and stress color contour plots.

Deformed geometry features provide the capability to view deformation results derived from a structural analysis of the finite element model. The user can display this deformed geometry by itself or superimpose it over the original undeformed model. In addition, because the deformations are typically small, a feature is provided to amplify the deflections in order to help distinguish them from the undeformed geometry. In Patran-G, the deformed geometry can be produced by using a "Run" command and adding adjectives to
the hidden line plot request. For example, the key-in "RUN, HIDE, NOERASE DEFORM = SUBCASE1.DIS" will create a hidden line plot (HIDE) of the deformed clutch pawl structure which is described by the results file subcase 1 (DEFORM = SUBCASE1.DIS) and will not clear what is on the screen previously (NOERASE). The output of this command is shown in Figure #4.47 for the clutch pawl in its maximum operating load condition. The significance of the no erase feature allows the user to plot the undeformed geometry first, as shown in blue. The deformed pawl, shown in red, is exaggerated by a scale factor. This scale factor is set to display the maximum deflection as one tenth of the maximum dimension of the model by default. This maximum deflection is actually 0.09 millimeters and occurs at the bottom left corner of the clutch pawl (node 13, element 380) as viewed in the figure.

Stress contour plots were also examined for the clutch pawl in the maximum load condition. This feature allows the user to convert a numerically intense nodal stress file into a descriptive graphical representation of the data. To assist in this task, Patran-G provides automatic scaling features and color assignment for varying levels of stress. The stress contour plot is initiated by the user with a key-in such as "RUN, CONTOUR, VON" which produces a contour plot of the VON MISES equivalent stress. Figures #4.4.8 and #4.4.9 illustrate the stress contour plots for the clutch pawl case study as viewed from various angles with the stress spectrum scale in newtons per square millimeter. The high stress area is quickly apparent through examination of these figures. To get a closer look at the high stress area, the active set in the
view is changed and zoomed in on. Figures #4.4.10 and #4.4.11 show the resulting plots of this area. The section view of this area indicates that the maximum stress is about 1.7 newtons per square millimeter, significantly below the yield stress of the material. Patran-G also provides a variety of labeling features in case the user would like to get additional information on the nodes or elements which relate to a specific area of interest. For example, figure #4.4.12 provides the element identification number for the high stress zone being examined on the clutch. These numbers would allow the user to be able to quickly relate the graphical information to detailed numerical output of the NASTRAN results file. In this manner, one can efficiently interpret finite element model results with graphics and complement that analysis with numerical data as required.
Figure #4.4.7 - Patran-G Clutch Pawl Deformed Geometry Plot

DEFORMED HIDDEN LINE PLOT

$CLUTCH\ PAWL\ SOLID\ @\ LOAD\ POSITION\ H_1$
Figure #4.4.8 - Patran-G Clutch Pawl Stress Contours - Isometric View
Figure #4.4.9 - Patran-G Clutch Pawl Stress Contours - Multiple Views
Figure #4.4.10 - Patran-G Clutch Pawl Stress Contours - High Stress
Figure #4.4.11 - Patran-G Clutch Pawl Stress Contours - Sectional View
Figure #4.4.12 - Patran-G Clutch Pawl Element Identification Plot
V. DISCUSSION

Through a literature survey, this paper reviewed the history of CAD and examined some of the more common CAD techniques being applied in the industry today. The capabilities explored started with basic automated drafting techniques, and then stepped back to geometry modeling methods which can be used to create a database that can support many CAD techniques beyond automated drafting. Within the geometry modeling hierarchy, the attributes of 3-D wire frame, surface, and solid geometry models were discussed. Next, a variety of CAD analysis tools were explored which included interference, mechanical properties, finite element, and mechanism analysis, along with a sample of customized CAD applications. Each of these segments briefly described the basic operation and advantages over prior techniques available to the product development engineer.

A case study of CAD was then described to develop a more comprehensive understanding of the typical system interface techniques. This case study represented a three year exercise conducted, over a time period from 1983-1985, by the author at Xerox Corporation using commercially available systems being offered at that time from Applicon, Intergraph, and Patran-G. For consistency, a plastic clutch pawl was selected as the benchmark design in which the three CAD systems operated on. The focus of the case study centered on the workstation hardware, interface methods, and brief examples of the operating procedures on each system from a user's perspective.
In order to set the stage to make some reasonable conclusions from this design thesis, some clarification is required relative to the case study. More specifically, a comparison needs to be made between the systems which were utilized. In addition, some discussion is required as to how the computer-aided design industry has progressed during the three years since when the case study was conducted. These two areas are addressed in the sections which follow.

5.1 Comparison of the Case Study CAD Systems

In the truest sense, a benchmark is more than a demonstration of a computer graphics system. It is a performance test that represents an example of current or potential applications that will be performed. Because of the unrehearsed nature of benchmarks, they enable users to analyze a system's ease of operation. A benchmark does not so much test design speed, but the way a certain system performs various design and engineering tasks. The case study conducted using the Applicon, Intergraph, and Patran-G allows benchmarking between the systems. The objective of this benchmarking is to analyze the basic user interface techniques utilized by the systems, and also to evaluate the systems capabilities.

Caution must be exercised in the benchmark analysis regarding the timeframe of the case study. Though each system was regarded as state-of-the-art at the time the case study was conducted, both the specific vendors, and the CAD industry in general, have undergone extensive improvements since that time. Also, due to the sequential nature in which the case study
was conducted on the various systems, it would not be valid to draw conclusions from this discussion as to which vendor is best at a given point in time. For example, Applicon introduced an enhanced system called "Bravo" at the same time the Intergraph system was being studied. Patran-G has also had numerous software system and hardware support enhancements since the release 1.5 software which was utilized in the case study.

5.1.1 User Interface

Human-machine interaction is a very important, but sometimes overlooked, facet of a CAD system. The interaction needed to make all of the features to work effectively is what really determines the system's usefulness. It is most desirable to have a user interface that makes a system easy to learn and use, yet provides sufficient power to fully control a complex CAD system.

In comparing the systems of the case study, several facets of human-machine interaction are considered. The four important aspects of user interface which were discussed include: effective use of the computer display, ease of information entry, capabilities which allow fast efficient operation, and prevention of unpleasant surprises and uncertainty.

The effectiveness of a user interface depends a great deal on the hardware and how well it is used. The computer's display is the focal point of the user's attention. Screen size, resolution, and color capabilities are key factors in determining the effectiveness of the display. In general, a larger high resolution screen with greater color capability allows the user to view a more
detailed image and get more of the design on the screen at one time. There is also more room for tutorial messages to help the user decide on how best to respond. In this respect, the Intergraph "Interact" workstation was the better of the systems used in the case study. This Intergraph workstation provided the greatest screen size using a dual screen approach with high resolution, and supports 32 different colors on one of the screens. The Applicon system and Patran-G/Tektronix 4109 were more closely matched. Screen size on Applicon was larger than the Tektronix 4109, but supported only 7 colors as compared to 16 on the Patran-G/Tektronix system.

In considering the aspect of ease on information entry, the goal is a user interface which is friendly, yet powerful. There are two sometimes conflicting goals here: the system must be simple for a novice to learn, but still be quick and easy for an expert to use. In the area of command entry, Applicon and Intergraph do a good job at meeting both these requirements. The sophisticated workstations utilized by these systems provide a tablet menu which can be used in concert with an alphanumeric keyboard and cursor. This method was far superior in the case study as compared with the menu hierarchy technique employed by Patran-G. The tablet menus had much of the speed of alphanumeric command entry, yet did not oblige the user to memorize command syntax or wade through menu levels. In addition, prompts were used much more effectively on the Intergraph and Applicon systems, though there is still room for improvement in this area.
Further distinguishing between the systems became apparent during the case study in the area of numeric and graphic input within a command sequence. Each of the systems used a similar alphanumerical keyboard approach for numeric input, but differed significantly in terms of graphic data input technique. Again, the more sophisticated workstations used in the Applicon and Intergraph systems were more powerful and simple to use than the Patran-G/Tektronix system. The keyboard or thumbwheel cursor control on the Patran-G/Tektronix system was much more cumbersome than the pen or cursor pad used on the Applicon and Intergraph systems respectively.

The third area of user interface which could be compared between the systems in the case study involves the speed and efficiency of operation. No matter how fast the computer is, there will be times when you must wait for some operations to finish. Capabilities which help minimize this waiting time will improve your interaction with a CAD system. These aids typically fall into the areas of item selection and temporary drawing simplification. Each of the systems provided a different approach to graphics item selection. Patran-G relies more heavily on identification numbers to select elements, whereas Intergraph and Applicon utilize interactive graphics techniques almost exclusively. For example, Intergraph utilizes various snap options in conjunction with the visual cursor and cursor pad buttons to help the user rapidly select graphic elements or locations. Similar in concept, the Applicon system uses a variety of pen stroke commands. The systems all have features to verify the selected elements or locations, be it cross hairs, butterflies, and/or element highlighting. Drawing simplifications features were also provided to
temporarily depopulate the drawing display and minimize visual complexity and tedious element selection. Patran-G did this through "active set" options and temporary "erase" function. Intergraph and Applicon provided "display depth" options and drawing "level" separation. After using each of the systems to create the case study clutch pawl, the features provided on Intergraph and Applicon were judged by this author to be much better suited to fast efficient interactive computer graphics operation.

The speed and efficiency of operation of the actual processor being utilized also had a major influence on the user's perception. Both the Intergraph and Patran-G systems utilized a DEC VAX based host processor, as compared with the Applicon system which used a DEC PDP-11 based host. Due to this fact, the Applicon system was disadvantaged with much slower processing speed. This was especially apparent in screen repaint operations. To get around this, the Applicon system provided the command to display changes only, and therefore, deferred complete screen repaint as long as possible.

The last major aspect of user interface was regarding the systems ability to prevent unpleasant surprises or uncertainty. Factors involved here include verification or elements being operated on, error prevention, and error recovery. In this respect the Applicon system was the only one of the three which gave the user the opportunity to undo the last command. Intergraph does provide verification prompts which allow the user to reset within the command operation until execution. Patran-G on the other hand had minimal verification or recovery features.
In total, from the case study experience, the features and capabilities of the Intergraph system was superior to the other systems relative to the user interface criteria described in this section. The Applicon system would be second, and Patran-G a distant third. This result is not surprising based on the workstation sophistication of Intergraph and Applicon. The Tektronix 4109 terminal, which was utilized to run the Patran-G case study, is more of a general purpose terminal and not specifically intended for extensive interactive CAD applications. In contrast, the Intergraph and Applicon workstations were designed specifically for this application and are sold as an integral part of their turnkey systems.

5.1.2 System Capabilities

In making a comparison of the case study systems relative to their capabilities, an evaluation can be made as to their flexibility, features, and potential productivity. The most desirable system, in this respect, would be the one which most effectively supports the design and development activity. A description of the most common CAD tools utilized in this design activity is presented in the survey contained in Section III and includes automated drafting, geometric modeling, and various design analysis techniques. It is important to note the timeframe in which these systems were utilized for the case study. Because of the rapid advancement in the CAD industry, these comparisons would not be accurate for these vendors current systems.
The Applicon system, which was utilized in the case study during the 83-84 timeframe, represented Xerox's initial efforts in the use of CAD for a complete product development program. In general, the Applicon system was applied as a substitute for manual drafting. The system's capabilities were limited to 3-D wire frame modeling and automated drafting. The Applicon system did not provide any significant design analysis capabilities. Therefore, high value added analysis applications required data translation, where possible, or geometry recreation for these specialized application systems. For example, a critical part design under high stress would require to have the geometry recreated on a system with finite element capability in order to perform the stress analysis. Of course, if the geometry could not be translated, a fully dimensioned drawing would be required for the geometry recreation. The result of such duplications, and the part optimization which followed as a result of the analysis, was that a significant amount of time and money was spent for such part designs. This high time and money investment made it impractical for all but the most critical designs.

The Patran-G case study was conducted in the 83-84 timeframe as well. Xerox licensed with PDA Engineering to utilize Patran-G principally for its finite element pre- and post-processor capability. In addition to finite element modeling, Patran-G also supported 3-D wire frame, surface, and solids modeling. This geometry modeling capability was much more sophisticated than the limited 3-D wire frame capability of the Applicon system. Though, because of the less powerful user interface of Patran-G (as discussed in Section 5.1.1), and its lack of automated drafting capability, both systems coexisted at
Xerox during this period of the case study. The respective strengths and weaknesses of these systems dictated the function they provided in the product development cycle. That is, Applicon was used chiefly for design layout and drawing creation, and Patran-G was used for finite element analysis. Similarly, other systems were utilized at Xerox to address needs not met by either Applicon or Patran-G. For example, DRAM (Dynamic Response of Articulated Machinery) was licensed from Mechanical Dynamics, Inc. to do mechanism analysis.

During the 85-86 timeframe, the Intergraph case study was conducted. The acquisition of Intergraph hardware by Xerox represented the companies desire to transition into a single vendor CAD/CAM solution. Though the capabilities of the Intergraph system utilized in the case study did not satisfy all the product development cycle needs, it was believed to be the most promising prospect toward meeting this challenge in the future. The case study covered the 3-D wire frame and surface modeling capability of Intergraph as demonstrated through the creation of the clutch pawl benchmark design. In addition, mass properties and automated drafting techniques were also explored. Beyond the system's mechanical design capabilities discussed in the case study, Intergraph offered less mature application packages in the areas of sculptured surface and solids modeling software, as well as engineering analysis software to do finite element and mechanism element modeling. Due to the immaturity of these applications packages during the time of the case study, Xerox did not believe them to be practical for use by the product development organization and did not install
the software packages on their Intergraph systems. Therefore, stand alone software packages, such as Patran-G, continued to be used for the specialized CAD analysis applications, like finite element modeling, until the Intergraph products were further developed.

In summary, the case study presented in Section IV showed a progression from 3-D wire frame, surface, and finally solids modeling capability with the Applicon, Intergraph, and Patran-G systems respectively. Though a comparison can be made from a geometric modeling perspective, one must recognize the systems each had different intended use from the supplier's vantage point. That is, the Applicon system represents a turnkey design/drafting system, Patran-G a specialized finite element pre- and post-processing software system, and Intergraph as a complete turnkey computer-aided engineering system. Therefore, the comparative value of each system will vary based on the intended environment for use, and the potential benefits which can be derived from each system's capabilities in that environment. Since this paper focuses on the use of CAD in the mechanical product development process, the conclusions section will describe the requirements of this environment and potential productivity impacts possible through the integration of CAD.

5.2 Progression of CAD Since the Case Study

The CAD industry is a rapidly changing field which is being fueled by technological advances in both hardware and software. Though the case study represented state-of-the-art systems during the 83-85 timeframe, some
discussion should be conducted relative to the more recent progression of the CAD industry. This section looks first at a macro view of the trends in the CAD industry as a whole. Then, a micro view is taken to look at the progression of Intergraph as an example of a successful company's progression in this industry.

5.2.1 General Industry Progression

Because of the great speed at which the CAD industry is evolving it is difficult for even experts to keep pace with the most recent advances. Great strides in application software capabilities, as well as hardware, is reshaping the way CAD is being applied in the industry. The ultimate direction of CAD, and the level of benefits which will be derived from its integration into product development, will vary by application and company. Whereas large high technology companies may be able to cost justify large turnkey systems, some small companies may migrate to the quickly emerging capabilities of PC-based systems.

Due to the dynamic nature of the industry, the best indicator of general trends can be drawn from statistics on the current and future markets for these systems. These trends can be separated into the areas of software applications and hardware.
A survey conducted over a wide range of product development industries was conducted in 1987 in order to determine both the usage and application trends in CAD. Figure #5.2.1 reveals the results of that survey [26]. At that time, 65% of the respondents were currently using the technology, and that figure was expected to grow to nearly 90% by 1990. On the applications of CAD, mechanical design and drafting was most popular with 90% of the respondents using it, or expecting to add the capability. In the up and coming CAD areas, solid modeling, finite element analysis, testing, and networking appear to be doubling over the next year or so. These results are consistent with the desired objective of an integrated system with a full set of capabilities. As solid modeling begins to become more widely available and functional, we will then be able to achieve the key goal of a common database which is complete enough to support the various CAD applications.

In the area of hardware progression, a major ongoing trend has been the development of high powered personal computer (PC) based systems. With the introduction of new 32-bit PC’s, there is less of a performance distinction between these units and low-end workstations. This new breed of PC’s can provide many of the same functions as the higher priced workstations, but suffer from being slower and lacking some of the graphics realism. This trade-off may be perfectly fine for users who are only looking for some of the basic applications like general drafting. A basic PC-based CAD/CAM system can be assembled for under $10,000 as compared to the higher end workstations which range from $40,000 to $100,000 per seat [27]. This trend is confirmed by examining the forecast of PC usage for general drafting systems which is
Figure #5.2.1 - CAD Usage Survey Results [26]

**CAD/CAM/CAE USAGE**

- Presently Using: 65.3%
- Expect in 1 year: 6.7%
- Expect in 1-3 years: 13.2%
- Not foreseeable: 12.3%

**CAD/CAM/CAE APPLICATIONS**

- Presently Using
  - Mechanical Design/Drafting: 7.4%
  - Graphics/Plotting: 62.4%
  - Electronic Design/Drafting: 11.4%
  - Math Analysis/Calculations: 11.7%
  - Finite Element Analysis: 21.0%
  - Numerical Control: 20.8%
  - Solid Modeling: 14.9%
  - Manufacturing: 8.3%
  - Data Acquisition: 12.2%
  - Testing (Including Prototypes): 7.7%
  - Robot Programming: 7.2%
  - Materials Evaluation: 7.3%
  - Other: 6.7%

*Percentages add to more than 100% because of multiple response.*
expected to climb to 95% by 1990, but only foreseen to claim 35% of the higher powered design and analysis applications.

5.2.2 Intergraph Progression
As a means of taking a closer look at CAD progression over the last few years, the Intergraph Corporation was selected as an example of a successful CAD vendor’s progression. Through the selection of Intergraph for this example, we can also develop some continuity with the case study, and see how their CAD systems have advanced in the industry from both a hardware and software perspective.

Intergraph, formerly M&S Computing, was founded in 1969 as an engineering consulting firm. Through their experience with flight simulators, the company transitioned into interactive computer-graphics systems in 1980. Jim Meadlock has served as President and Chairman of Intergraph since its inception in 1969 and saw the possibilities for such graphic systems when hardware prices began to drop. During this time, the company’s revenues have grown from $56 million in 1980 to $640 million in 1987. Intergraph is now only second to IBM in both CAD system revenue and market share [36].

Much of Intergraph’s early success has been attributed to their selection of Digital Equipment Corporation computers as a standard hardware platform for their initial turnkey systems. Because of this relationship with DEC, Intergraph was also able to make the move from the old PDP-11 based system to the new VAX line long before other vendors. This came at a time when
competitors like Applicon and Computervision were selling CAD systems based on proprietary hardware. Intergraph also established an edge on the competition, from a hardware perspective, through the development of engineering workstations, in addition to host-based systems. In 1984, when some vendors were just realizing that engineers wanted stand-alone hardware, Intergraph was already marketing the InterPro 32, a single-user, 32-bit system. The company’s workstation line has since expanded to include a dual-screen "Interact", similar to what was used in the case study.

Intergraph has also been quick to incorporate the latest technologies in their workstation hardware. This was demonstrated with the introduction of the "Clipper" based processor 32C Series of stand-alone engineering workstations, as well as the more recent 200 and 300 Series. Though competitors have had problems with market acceptance of proprietary hardware, Intergraph has been careful to insure their systems compliance with software standards such as Unix System V, Ethernet, Windowing Systems, etc. By employing industry standards, Intergraph systems have much greater flexibility in terms of compatibility, as well as allowing third parties to develop software within a standard Unix environment.

Intergraph has also responded to the industry trend toward PC-based systems by purchasing 50% interest in a PC CAD company. They now own exclusive marketing and distribution rights to Micro Station design and drafting software, first developed in 1986 by Bently Systems, Inc. This program runs under DOS on IBM PS/2, PC/XT/AT and compatible computers, and sells for
Designs created with Micro Station are compatible with Intergraph VAX and Unix-based applications without translation. Therefore, the purchase of Micro Station will let Intergraph compete in the PC CAD environment, but more importantly, it provides inexpensive entry into larger Intergraph systems. Intergraph's hardware strategy is for most of their traditional CAD applications to be eventually moved to a workstation environment, with hosts providing data base management and computationally intensive applications [38].

In the area of software development, Intergraph has developed a highly regarded reputation due to the breadth of its software line which covers more applications than anybody else. Their application software includes a full range of packages for a mechanical and electronics design, architecture, mapping, civil engineering, electronic publishing, utilities, geophysics, and facility management. Intergraph's most significant progression in software development since the case study came with the introduction of their written-from-scratch "Intergraph Engineering Modeling System" (I/EMS) in 1987. This is a mechanical design package that integrates wire frame, surface, and solid modeling with full detailing capability for drafting [39]. The technical significance of this introduction is that, while other systems merely define part models in terms of point, lines, surfaces, and volumes, I/EMS uses so-called object-oriented programming techniques and data structures. This object oriented database integrates geometry with attribute data, and also captures and maintains the real-world relationships between model elements.
By the nature of the associative geometry model, the system "knows" the identity and behavior of the individual elements, as well as the environment in which it fits. This is significant in that all the information resides in a unified database. This goes beyond the conventional method of capturing geometry and simple descriptive data, to storing mathematical and logical relationships in an "intelligent" model. The creation of a unified object-oriented database using I/EMS facilitates downstream analysis and manufacturing operations. In addition, object-oriented databases are also being used as the basis for work in applying artificial intelligence and expert systems to mechanical design. Because the system can recognize objects and the relations between objects, design rules can be imbedded in the software to compare the configuration with that of a standard specification.

Intergraph's engineering modeling system uses non-uniform rational B-splines (Nurbs) as the common mathematical representation in wire frame, surface, and solids. As was discussed in Section 3.2.2, the use of Nurbs is one of the most efficient ways of defining both simple and complex geometric elements in the computer. Through this approach, a reduced-instruction set computer (RISC), like the Intergraph clipper-based workstations, can be used to simplify computing and increase speed. Implementation of Nurbs also provides greater flexibility for local modifications, as well as allowing wire frame, surface, and solid elements to exist in the same model.

The combined hardware and software strategy Intergraph has set for their future is consistent with the industry trends discussed in the previous section.
Intergraph has established a full range of compatible workstations ranging from low end PC-based systems to high powered host-based systems. In addition, I/EMS software has provided the foundation for a unified database which can take advantage of the latest hardware technologies and support a wide range of mechanical product development CAD needs.
VI. CONCLUSIONS

It is quite common to see computer-aided design referred to as the most significant advance since the development of electricity. In this context CAD has been professed as the greatest breakthrough of modern times in the search for ways to improve the product development process. These claims for improvement are based on the ability of the engineer utilizing these tools to bring to market better quality and higher performance products in a significantly shorter design/development cycle, and at a lower cost. The previous chapters in this paper included a survey and case study of how some of the more commonly used CAD techniques can be applied to automate specific tasks that a mechanical engineer encounters in developing a product. However, to adequately examine the bold claims surrounding CAD, one needs to look at the overall impacts it has on the product development cycle. Utilizing the knowledge gained through the CAD survey and case study as a foundation, the conclusions section of this paper will test the hypothesis that CAD techniques can significantly improve the mechanical product development process. To do this, the specific CAD techniques presented in this paper will be examined relative to the projected time and cost benefits possible through their integration in today's product development process. In addition, the industry trends and progression discussed in Section 5.2 will be examined relative to the outlook for further improvements in the future.

Prior to testing this hypothesis, a brief description of the basic elements within mechanical product development process is required. To accomplish this task, the mechanical product development process can be viewed as a
three dimensional matrix. This matrix, as represented in Figure #6.1.1 [22], consists of a variety of engineering applications and traditional functions which must be repeated for each developmental phase of the design. These developmental phases start with conceptualization, and move through initial design, detail design, design verification, pre-production engineering, production engineering, and finally, release to manufacturing. During each developmental phase, the engineering functions which need to be conducted include design, analysis, test, drafting, engineering documentation, project management, data management, process planning, tool design, numerical control, and quality control. The engineering applications for these functions include packaging, performance, structural integrity, reliability, producibility, and costs. Almost every block of the matrix is required to develop a product, and each block involves tasks that cost money, consume time, and have potential for errors and delays.

In addition to the developmental costs for the product, there are also the production costs and operations costs to consider. These production and operations costs are driven by the unit manufacturing cost, service cost, warranty cost, etc. In terms of the total life cycle cost of a product, the production and operations costs typically represent almost 80% of the total. This is a critical point to recognize due to the fact that the product design attributes, which are defined early in the development of the product, will dictate most of the cost required for production and operation. This relationship is illustrated by the graph in Figure #6.1.2 [40] which plots the committed cost and spent cost, as a percentage of the total life cycle cost.
Figure #6.1.1 - Product Development Process Matrix [22]
Figure #6.1.2 - Product Life Cycle Cost vs. Time [40]
versus time. The significance of this relationship is highlighted by the observation that typically less than 5% of the total life cycle cost is spent in the concept phase of the product development cycle, even though its outcome will determine 70% of the committed cost for the product.

A company, to improve its product development process significantly, must identify and improve the combination of applications and functions within the design phases which most critically impact success. From the added insight gained through this description of the product development process, and its relationship to committed cost, one must recognize that the greatest leverage for such improvement lies in the early phases of the process. Therefore, the emphasis for evaluating the hypothesis of CAD's impact on the product development process will focus on the conceptualization, initial design, detail design, and design verification phases. The main engineering functions which were addressed in the CAD survey and case study work include the design, analysis, test, and drafting functions. To perform each of these functions, the product development engineer has the opportunity to utilize automated CAD techniques in the applications areas of packaging, performance, structural integrity, reliability, producibility, and cost. The development cost and time impact of these specific CAD techniques, as compared with traditional manual methods, can now examined for the various phases of the product development cycle. The knowledge gained through the CAD survey and case study can be utilized to confirm that these conclusions are reasonable.
Starting in the conceptualization phase, new ideas are formulated and evaluated. Engineers typically want to define geometry quickly and perform rough analysis to decide which solution warrants further development. A CAD approach to this conceptualization phase would begin with the creation of geometric models to represent the various product design concepts. Within the area of geometric modeling, the specific benefits gained by utilizing the CAD system will vary based on the level of modeling sophistication which is applied. For example, a system limited to 3-D wire frame modeling will not have the ability to provide a realistic shaded image of the concept, as would a surface or solid model. This progression from wire frame to surface and solid geometric modeling capability was demonstrated with the clutch pawl design in the case study using the Applicon, Intergraph, and Patran-G systems respectively.

Realistic images of the various concepts help an engineer to satisfy the packaging requirements of the design in terms of interference detection, space boundaries, and even appearance considerations. Though there is not a significant time savings in the initial creation of a geometry model, as compared with a manual layout, there is certainly a significant improvement in communication effectiveness, accuracy, and the ability avoid costly errors. Manual layouts, for example, make it very difficult to identify interferences as compared with surface or solid geometry CAD models. In addition, modification of the geometry is much quicker with the CAD system as the different concepts are iterated. The efficient communication of the design concepts with other functions in the product development group allows
producibility and cost assessments to occur much earlier in the process as well.

The various analysis techniques available in the CAD systems environment then provide the engineer with the tools to test and evaluate the performance, structural integrity, and reliability characteristics of the concepts. Applications packages like mass properties, finite element modeling, and mechanism analysis can be used to quickly screen out concepts which are not feasible. The CAD applications packages, as illustrated in the survey, can also span areas from aids to spring, cam, or gear design, to more specialized applications like the paper path simulation. Such tools can substantially increase the quality of the design, while drastically reducing the design time. By automating manual pencil-and-paper methods through CAD, conceptual designers can try many more alternatives in less time. With built in analysis tools, the design can theoretically be optimized before a prototype is made. In addition, the geometry model and other information created during this concept phase can be passed to downstream functions.

As one example of the CAD analysis techniques which are available, the case study utilized the Applicon and Intergraph systems for mass properties analysis. Though each system provided an automated means to determining mass properties which was superior to manual methods, the level of automation varied based on the system capabilities and the level of geometric modeling being used. That is to say, determining mass properties for the clutch pawl using the wire frame model on the Applicon system required twice
as much operator interface than was required for the surface model on the Intergraph system. Further, similar mass properties information could have been determined from the solid model created on Patran-G system with one simple command.

A more complex example of CAD analysis techniques was also demonstrated through the finite element model structural analysis which was conducted on the Patran-G system. In the past, finite element models were constructed through very cumbersome and error prone numerical data input techniques. This made early concept design analysis impractical in many cases, and typically resulted in over-design of critical stress areas, poor cost-effectiveness, and high failure rates. Now, interactive graphics finite element pre/post-processors, like Patran-G, have simplified both model creation and analysis interpretation. CAD analysis applications, similar to the finite element structural analysis conducted on the clutch pawl, allow engineers to confidently test and optimize part designs prior to actual fabrication. The clutch pawl exercise demonstrated the capability for an engineer to develop a part design which did not exceed stress or deflection requirements, while minimizing the rotating pawl inertia for performance, and decreasing the part’s material usage for cost.

Once the various concepts have been investigated, the initial design phase of the product development process is conducted. This phase represents an evolution of the product design through the selection of the most promising concepts as a result of the early analysis. The initial design phase basically
Section VI

Conclusions

consists of a more detailed execution of the same functions and applications carried out in the conceptualization phase. Since the CAD environment easily facilitates change, the product development engineer uses the geometry model created in the conceptualization phase as the starting point for the initial design. Guided by a more comprehensive application of the same CAD analysis techniques as discussed in the previous phase, the concepts are matured into a complete product design. This complete design may include some elementary design components, like standard hardware or components, which were deliberately left out of the concept analysis. The CAD survey illustrated the Intergraph screens which support this application through the use of standard component libraries stored on the system. Not only can these tools help save time for the engineer or designer in creating the initial design, they can also minimize the number of unique components used. This is just one example which has long term implications in terms of reduced product, inventory, and service costs.

Since the initial design phase requires more input from the various engineering support personnel and suppliers in order to mature the design, the ability to effectively communicate the latest design configuration is very important. CAD provides the capability for each of these individuals with system access to view the latest design information on which to base their input. Communication with outside personnel can also supported through the use of networking arrangements or with hard copy plots of the geometry models. Comparable manual methods at this phase of the product development cycle would merely consist of a set of two-dimensional layouts.
with key control dimensions. These layouts are much less efficient for communications. In addition, due to the lack of integrated analysis and test capability using the manual methods, some early prototype hardware fixtures typically are required in order to evaluate a limited set of critical design concepts. Therefore, some preliminary drawings would need to be created to support both the communication and early prototype fabrication process. As a result of these manual method limitations, the CAD approach begins to clearly show some cumulative benefits in terms of cost, time, and enabling a more mature design to be established earlier in the product develop process.

When the initial design has been completed, CAD systems now provide an automated means to detail drawing creation. As discussed in the CAD survey section, there is some debate as to whether there is a significant difference in the time required to create a detail drawing from scratch manually versus on a CAD system. Though, this debate does not apply when one considers that the geometry model, or CAD layout, already exists as a starting point for the detail drawing creation. Under these conditions, automated CAD drafting packages will consistently save drafting time, and also reduce errors, by using the actual geometry model as the basis for the drawing creation. The case study on the Applicon and Intergraph systems discussed these automated drafting features as examples of how they are applied on CAD systems today. The CAD approach also provides some incremental benefits when one considers the speed enhancement of making future changes to these CAD drawings. In addition, CAD generated detail drawings are viewed in the industry as being much more consistent and uniform.
After the detail design phase has been completed, the product development cycle moves to the first prototype model build of the entire product as a means of design verification. During this design verification phase, the detail design information is utilized as the vehicle for completely describing all the parts and assemblies which make up the product. The main activities within the design verification phase include part fabrication, assembly, debug, and test.

The discussion in the previous phases indicates how the CAD tools have helped clear the way for this phase by reducing the propensity for errors which can cause costly delays. The realistic images available through the use of solid and surface modeling techniques in the earlier phases can also be utilized in this phase to assist in part visualization for fabrication, assembly, and service. For example, some vendors are willing to knock 10 to 25% off the price of complex tools if they are provided with color shaded image of the model beforehand. The color shaded images of the clutch pawl in the Intergraph and Patran-G case study illustrated these visualization benefits.

In addition to the CAD applications on which this paper is focused, the geometric model can be applied to computer-aided manufacturing (CAM) techniques. These applications consist of such things as flat pattern development, automatic tool path programming, mold flow analysis, etc. Though these CAM techniques are outside the scope of this paper, they do represent significant benefits which must be considered in a fully integrated CAD strategy toward product development.
The final product development phases include that of pre-production engineering and release to manufacturing. Since these phases are simply an additional design iterations, the similar applications previously described in this section would apply. The important point to note during these later phases is that the cost of design change increases as the product approaches manufacturing. Therefore, the ability to optimize the design and detect problems early in the design process is critical.

As a means of summarizing the impacts of these CAD techniques on the various product development phases, as compared to manual methods, a graph of cost versus time is shown in Figure #6.1.3 [22]. These top two plots demonstrate the general extent to which the product development cycle can be made more efficient, in terms of the cost and time required to develop a product, through the use of CAD tools available today. These improvements were confirmed by the techniques described in the CAD survey, as well as the examples presented in the case study. From this analysis one can accept the hypothesis that the use of CAD techniques can significantly improve the mechanical product development process.

It is also apparent, from the knowledge gained through this design thesis, that there is a much greater opportunity for improvement yet to come as these CAD methods evolve in the future. These additional benefits available through the CAD automation of tomorrow are projected in the lower plot of Figure #6.1.3 [22]. These further improvements in the cost and time required to develop a product represents a movement toward a fully integrated
Figure #6.1.3 - CAD Time/Cost Benefits vs. Manual Methods [22]
approach to the application of CAD with greater emphasis on the up front analysis during the critical conceptualization phase. The "Island of Automation" syndrome of the 1970's, caused by proliferation of incompatible computer systems, still remains a key obstacle to companies that try to purchase integrated CAD systems today. The most important advantage of a truly integrated CAD system involves the ability to use one central database for all the product development functions. This single database would include the geometry and physical properties description of all the components and subassemblies which make up the product. This integrated CAD system would allow the user to input the data once, utilizing a geometry modeling technique, and then move it through the various analysis techniques such as interference, mechanical properties, finite element, mechanism, etc., and eventually automated drafting to produce the detail drawings. Also, as changes are made in the design as it matures, all users are certain to be using the same configuration when a common database is maintained.

This movement toward an integrated systems approach was the underlying theme which came out of the study of the CAD industry progression in Section 5.2. The specific trends highlighted in the CAD industry survey indicated a rapid growth in solid modeling, analysis, testing, and networking capabilities. In recent years great strides are being made by CAD vendors in the area of integration. In fact, some of the larger turnkey vendors are quickly approaching systems which offer a full array of modeling, drafting, and analysis capabilities with functionality similar to the systems which specialize in just one area. The Intergraph progression, also described Section
5.2, confirmed these same trends through the introduction of their higher power workstations, network capability, and I/EMS software. Further, this object-oriented geometry modeling software by Intergraph demonstrates the foresight of expanding CAD system capabilities to include artificial intelligence in the future.

The case study experience also confirms the opportunity for improvement through the use of an integrated CAD system approach. Though each system which was utilized in the case study clearly demonstrated some benefits over traditional manual methods, neither of the three state-of-the-art systems tested provided the desired capabilities. For example the clutch pawl geometry created on Intergraph had to be recreated on the Patran-G system to conduct the finite element analysis. Similarly, if a mechanism analysis was desired, a third CAD system would have to be used. To overcome the lack of this ideal system, today many companies are forced to use translation programs, where available, or recreate the database on the various systems. Beyond the disadvantages of geometry recreation or translation, the training required by the author for the CAD systems utilized in the case study averaged approximately 60 hours per system. More importantly, the amount of time to reach a proficient level of operation on a CAD system is believed to be on the order of 6 months for a full time user, and possibly not achievable for part time users. These problems would certainly be overcome with the integrated systems approach.
As this level of full system integration is reached, the CAD and CAM functions are also being brought together in what is commonly referred to as computer-aided engineering. Computer-aided engineering (CAE) is the product design and development philosophy of integrating the key engineering, design, test, analysis, drafting/documentation and related manufacturing functions into each phase of the mechanical product development process.

In summary, despite its hair-raising growth and expanding capabilities, computer-aided design (CAD) is still evolving. Industry trends indicate a day will come when products can be built and tested on a screen [25]. Future product development engineers will be able to tell in advance of building actual prototypes whether or not their end product will perform as required. Until that day arrives, this design thesis has confirmed that engineers of today can make significant progress by putting their CAD systems to work in automating specific parts of their mechanical product delivery process.
REFERENCES


REFERENCES
(continued)


REFERENCES
(continued)


<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>AXIS POINTS: 0.0000, 0.0000</td>
<td></td>
</tr>
<tr>
<td></td>
<td>1.0000, 0.0000</td>
</tr>
<tr>
<td></td>
<td>4.0000, 4.0000</td>
</tr>
<tr>
<td>PRECISION PARAMETER: 50.0000</td>
<td></td>
</tr>
<tr>
<td>SOLID OF CONSTANT THICKNESS:</td>
<td></td>
</tr>
<tr>
<td>THICKNESS: 1.5000</td>
<td></td>
</tr>
<tr>
<td>DENSITY: 0.9914</td>
<td></td>
</tr>
<tr>
<td>VOLUME: 883.7067</td>
<td></td>
</tr>
<tr>
<td>WEIGHT: 1.2540</td>
<td></td>
</tr>
</tbody>
</table>
AXIS POINTS: -3.6340, -2.6660, 19.0000
      -3.1740, -15.1230, 19.0000

PRECISION PARAMETER: 50.0000

--SOLID OF CONSTANT THICKNESS--

THICKNESS: 1.5000

DENSITY: 0.0014

VOLUME: 177.51593

WEIGHT: 0.2519
Appendix I

Applicon Mass Properties Graphics

AXIS POINTS: 0.0000, 0.0000, 0.0000

PRECISION PARAMETER: 50.0000

SOLID OF CONSTANT THICKNESS:

THICKNESS: 12.0000

DENSITY: 0.8014

VOLUME: 647.7820 3

WEIGHT: 0.9192
AXIS POINTS: 4.1750, -1.6690, 0.0000
      4.0930, -1.6780, 19.0040

PRECISION PARAMETER: 50.0000

--SOLID OF CONSTANT THICKNESS--

THICKNESS: 1.5000

DENSITY: 0.0014

VOLUME: 178.20093

WEIGHT: 0.2529
AXIS POINTS: 0.0000, 0.0000, 21.0000
1.0000, 0.0000, 21.0000

PRECISION PARAMETER: 50.0000

--SOLID OF CONSTANT THICKNESS--

THICKNESS: 2.0000

DENSITY: 0.0014

VOLUME: 381.2418 3

WEIGHT: 0.5410
AXIS POINTS: 0.0000, 0.0000, 8.0000
               1.0000, 0.0000, 8.0000

PRECISION PARAMETER: 50.0000

--SOLID OF CONSTANT THICKNESS--

THICKNESS: 8.0000

DENSITY: 0.0014

VOLUME: 1923.9212 3

WEIGHT: 2.7302
<table>
<thead>
<tr>
<th>Description</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Precision Parameter: Solid</td>
<td>0.0015</td>
</tr>
<tr>
<td>Thickness</td>
<td>0.0004</td>
</tr>
<tr>
<td>Density</td>
<td>0.0014</td>
</tr>
<tr>
<td>Volume</td>
<td>47.00493</td>
</tr>
<tr>
<td>Weight</td>
<td>0.0076</td>
</tr>
</tbody>
</table>
NAME
VOLUME
MASS
MXX
MYY
MZZ
MXY
MXY
MZZ
LEFT-SIDE
1.75
0.25
0.249778
7.10659
5.05868
2.14840
-0.703545E-01
-1.62059
0.555814E-01

A-2
<table>
<thead>
<tr>
<th>NAME</th>
<th>VOLUME</th>
<th>MASS</th>
<th>MXX</th>
<th>MYY</th>
<th>MZZ</th>
<th>MXY</th>
<th>MYZ</th>
<th>MZX</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>PARTIAL-TAB</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>31.2500</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0.445313E-01</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0.850423E-01</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0.123698</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0.850423E-01</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0.000000E+00</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0.000000E+00</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0.309245E-01</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>