Interactive 3-D Models for Enhanced Classroom Instruction

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Abstract ? This paper describes the development and use of several interactive 3-D models for use in Fluid Power, Fluid Mechanics, and Machine Design courses. Instruction in these subjects often involves interpreting static 2D representations of complex mechanisms and flow paths that are important in reinforcing students' understanding of theoretical concepts. The addition of 3-D modeling allows students to better understand the internal structure and operation of pumps, valves and similar closed mechanisms that cannot be viewed directly during operation. Several models are presented, along with the instructional concepts the models are intended to illustrate.

INTRODUCTION

Communicating practical engineering subjects in the classroom frequently involves not only mathematics, but also the construction and operation of complex mechanical constructions. This is especially the case for instructing in fluid power, fluid mechanics and machine design. The tools to communicate these constructs have typically been the diagram, model and cutaways of actual equipment. Diagrams are static and therefore require the student to mentally move components or trace out flow paths. Models and cutaways can be difficult to obtain, maintain and finance although they are much better at helping the student to understand complex mechanical or fluid principles.

With the trend in industry towards 3-D modeling (3-D CAD or Computer Aided Design) and Computer Aided Analysis (CAE), the tools to create and present live 3-D solid models and perform the analysis thereof have come within the reach of the average instructor and school. It is now possible to create a 3-D CAD model, manipulate the moving components in real time, and analyze the relevant behavior of the components or fluids passing through the mechanism. Most instructional institutions also have the means to present the results of these simulations in a classroom setting. Thus the student can benefit from seeing a representation of a 3-D in ways never before possible.

MECHANISMS

Many engineering textbooks are filled with illustrations that diagram mechanisms. These diagrams hark back to the days of the pencil, T-square and drawing board. Some more modern textbooks will have illustrations produced by 3-D CAD systems. For the foreseeable future the printed page will be static and 3-D objects printed there will be static. The reader can neither turn them to view them from other perspectives nor zoom in to view detail nor slice them open to view the internal workings or remove intervening unnecessary detail. Ironically, this paper will use 2D printed graphics to illustrate what can be done much more quickly with live 3-D graphics.

A 3-D CAD system can not only create illustrations that can be rotated zoomed and sectioned during instruction. It can also create such illustrations that can be incorporated into small self-displaying files that can be given to students for markup.

When instructing subjects like hydraulics it is frequently the case that the movement of a mechanism is tied into movement of a fluid through the mechanism. While simple hand operated devices like globe and gate valves are not hard to understand from a static illustration, more complex devices like servo valves, pressure relief valves, compensated flow control valves and the like are much more difficult to understand. In these cases a 3-D CAD model coupled with a Computational Fluid Mechanics (CFD) model of the fluid flow through the passageways can greatly aid in understanding the principles of operation. Such models offer capabilities that even a physical cutaway cannot provide since with a cutaway fluid cannot be made to flow appropriately through the mechanism and without the cutaway portions it is impossible to see inside the mechanism. While clear plastic models of fluid devices can be made, they are expensive, messy and don't lend themselves to group observation.

Four bar Linkage

As an example of using 3-D CAD software to illustrate a mechanism a simple four-bar linkage will be explored. Figure 1shows a side view of a four bar linkage depicted in a 3-D CAD system (SolidWorks). This particular CAD system uses standard Windows format to present information to the user. Along the top of the window is a title bar with the active document name. Below that is a menu bar from which all functions of the software can be accessed. Below the menus is an area for user positionable toolbars. Toolbars can also be positioned to the left, right and bottom of the main window. A toolbar can also be undocked and floated over the window. On the left side of the screen is an area that can

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variously have a feature tree window, a property manager window, a configuration manager window, and any other special management window needed for added in applications. The feature tree and configuration manager use the familiar Windows node and tree system to manager data. To the right of the feature management window is the main window containing the graphical view of the 3-D model, in this case a four bar linkage.
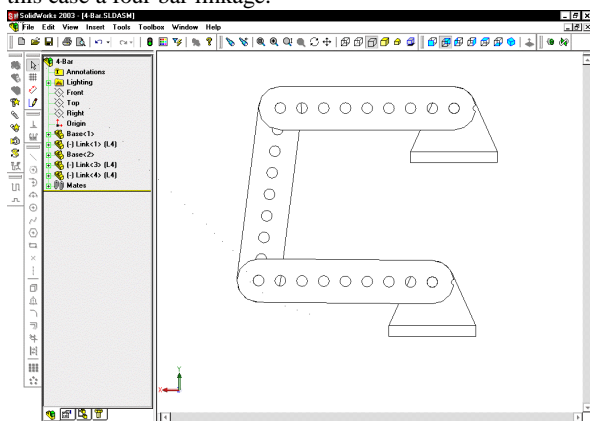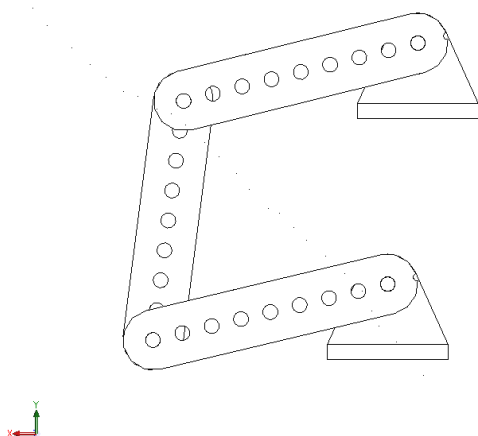

FIGURE 1

FIGURE 2

The four bar linkage model (see Figure 2) is an assembly of only two CAD models or parts. There is a base made to look like a triangular fixed pivot commonly used in text illustrations and there is a link with multiple pivot holes. The link can be attached at any one of the small holes along its length so as to pivot about another part. The link part actually contains a number of configurations that can be used to change its overall length. Configurations are changed by bringing up a context sensitive menu in the graphics area with a right mouse click (see Figure 3). The highlighted menu pick leads to a dialog box that allows the user to select any of the predefined configurations of the link (see Figure

4). When a different configuration is picked the link changes accordingly. In the case show the linkage is changed from equal length four inch arms to unequal length three and four-inch arms (see Figure 5).
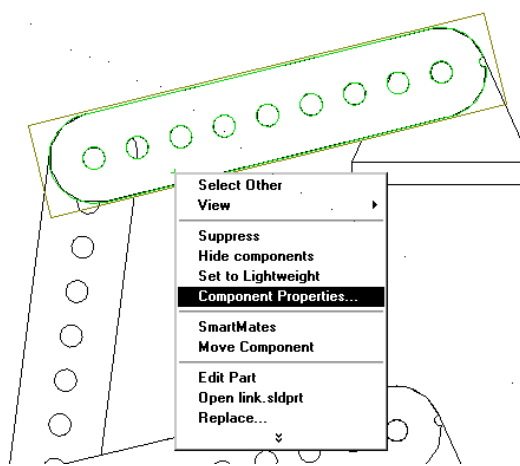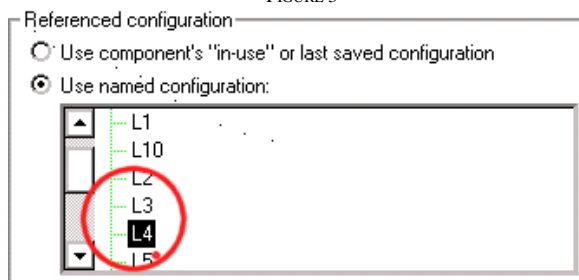

FIGURE 3

FIGURE 4

The previous example shows how it is possible to quickly and easily change the geometry of a simple linkage on the fly in order to demonstrate the effect of a change in relative arm length has on the behavior of a four bar linkage. To further demonstrate this effect the software allows the instructor to "grab" onto the arm and rotate it about its pivot. There is a menu pick shown in Figure 6 called Move Component designed for this purpose. When Move Component is active any component displayed in the graphics area can be grabbed and moved about any free degree of freedom. The entire assembly will then correctly show how all the parts would move together when one of the connecting parts is moved.

When moving parts of an assembly it is further possible to demonstrate certain simple kinematic effects such as a collision between two or more parts. In Figure 7 the Move Component Property Manager is shown with the Physical Dynamics capability enabled. This prevents two or more components from penetrating each other. In the case of Figure 8 the link is colliding with the base and will not penetrate it simulating the actual behavior of a real object.

With these simple tools any number of mechanical linkages can be demonstrated in class and the instructor has full control of the movement of the components. The configuration of various linkages can be quickly and easily changed to demonstrate the qualitative effects in a near real world scenario.
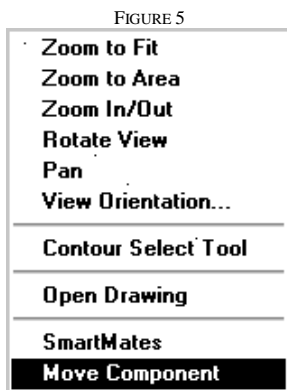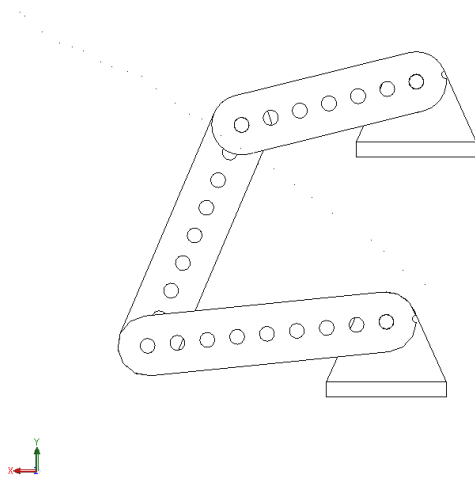

FIGURE 5

FIGURE 6

Universal Joint

The previous example showed a four bar linkage, an essentially 2D construction for which the primary advantage of displaying it with a 3-D CAD system was that it could be easily moved through its full range of motion. Three dimensional mechanisms like the universal joint are just as easily displayed on a 3-D CAD system and can be operated through their full range of motion allowing the instructor to demonstrate them not only in operation but also in their forbidden operating zones.
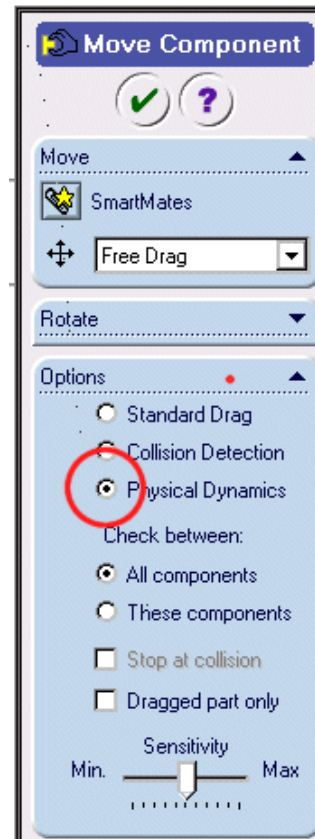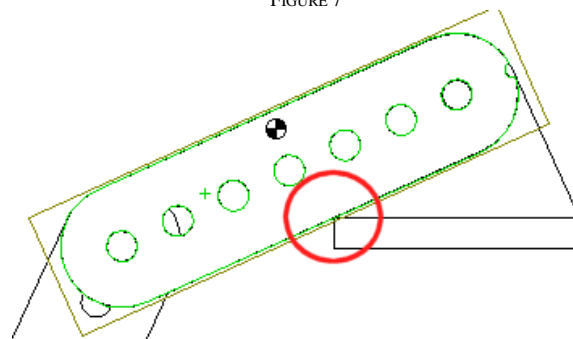

FIGURE 7

FIGURE 8

Figure 9 is used to depict a universal joint in its normal operating range. The highlighted green portion is active and is designated as the driver yoke to which a driving force would be applied. The unhighlighted portion is designated as the driven portion or output portion of the universal joint. Both yokes and the spider are clearly visible and can be viewed from any angle by a simple mouse drag. The student will therefore be presented with a visual depiction that is at once intuitive in depicting operation and representative of this class of joint as it is commonly manufactured. Thus both

the ability to learn the operation as well as to identify its real world counterparts can be presented concurrently.
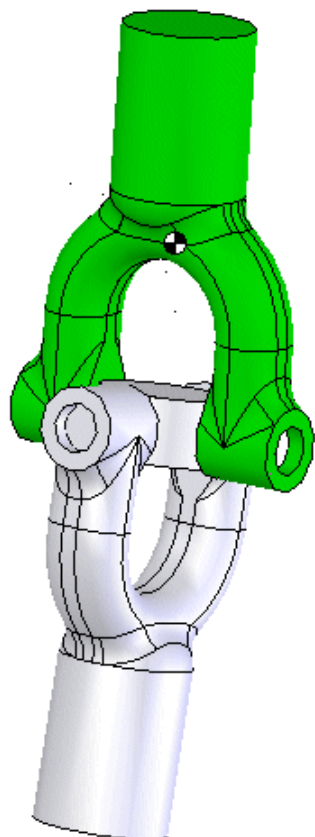

FIGURE 9

FIGURE 10

Figure 10 shows the universal joint in one of its forbidden positions. It should be clear at a glance that rotations of the driving yoke would cause no rotation of the driven yoke and would lead to the driving yoke colliding with the driven yoke. Figure 11 likewise shows that the joint in the other extreme forbidden position. It should be clear that in this position the driving yoke would tend to drive the driven yoke not about its axis of rotation but instead in a plane through its axis of rotation. Finally Figure 12 shows the universal joint assembly in a fixture that allows various angles of operation to be explored. In the animation the nutation of the spider is very apparent by zooming in on that area while the joint is rotating. Graduations have been added to the brackets and an arrowhead to the ends of the yokes to allow a visual determination of output rotation angle versus input rotation angle. The instructor can quickly generate data in class that can be plotted to show the input-output rotation variation for various joint angles.
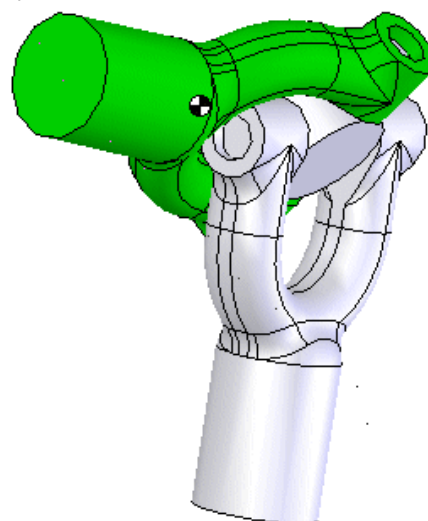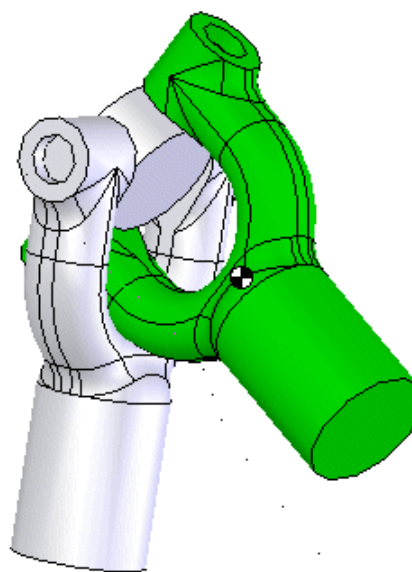

FIGURE 11

is made visible through the solid model to enable the student to see the entities that control the 3-D geometry. Figure 15 shows the cam ring moved to the extreme right. The cam ring can also be moved to the extreme left to show how vane pump flow might be reversed.
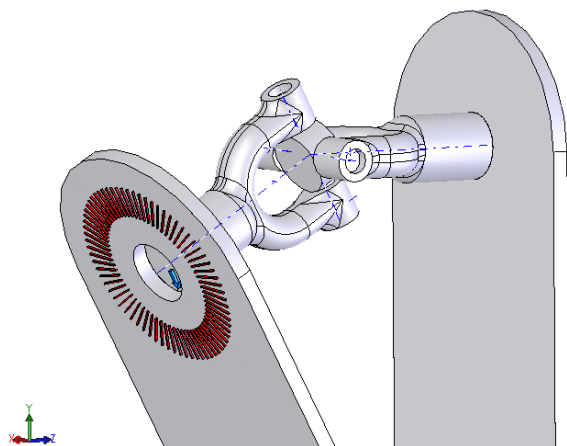

Figure 12

MIXED MECHANISMS

Instructing hydraulics frequently involves understanding not only fluid principles and equations but also the interaction of complex mechanisms with fluid flow. This is true for devices that are used to input and output fluid power as well as devices used to control fluid power. For the purposes of this paper these mechanisms will be called mixed mechanisms because they mix the principles of mechanics with the principles of hydraulics and fluid flow.

Vane Pump

Vane devices are widely used as both pumps and motors in hydraulic and pneumatic devices.   A vane device functions by having a series of sliding vanes attached to a rotor and in contact with a cam ring create compartments which fill and then expel fluid by changing volume as they rotate within the eccentrically disposed cam ring.   The eccentricity of the cam ring and the difference in diameter of the rotor and the cam ring control the volumetric displacement per revolution, the key parameter used in pump/motor calculations.

It is not always easy to visualize the operation of a vane device from static diagrams. Figure 13 shows simple model of a vane device. It consists of a rotor, vanes, cam ring and valve plate. The position of the cam ring is controlled by a layout sketch in the assembly and it can be moved from the neutral position to the full eccentric position by means of a single change in a dimension. The layout sketch also controls the ID of the cam ring and the OD of the rotor enabling standard calculations for volumetric displacement to be performed.   Figure 14 shows the operation of the layout sketch. A dialog box is open which changes a dimension controlling the offset of the cam ring. The sketch
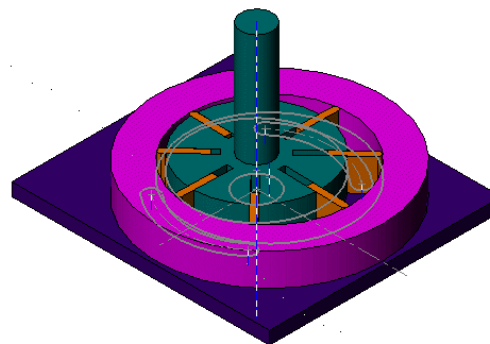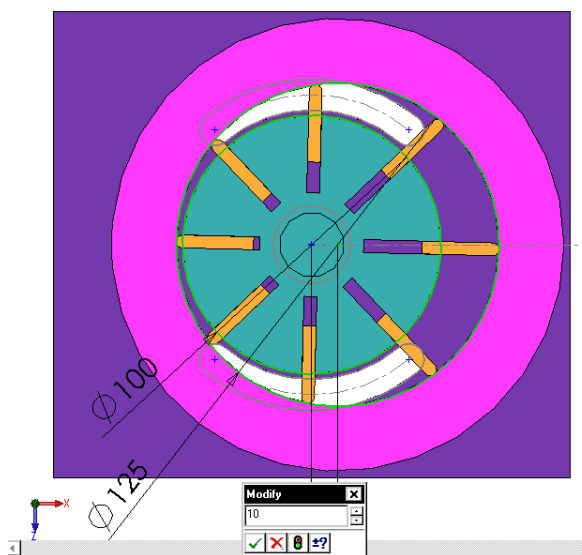

FIGURE 13

FIGURE 14

The vane pump can also be animated to show dynamically how the chambers formed between the cam ring, rotor and vanes increase and then decrease in volume and thus convert fluid flow into rotary motion and vice versa.   Figure 16 shows the toolbar associated with animation. The left column of buttons shows the standard controls used to record and playback an animation. The right column shows a detail view of the buttons used to apply force, rotation, springs or gravity to components. There are no units associated with these controls as they were intended for illustration purposes only. The amount of each quantity is

controlled by a slider visible in the property manager window for each control.
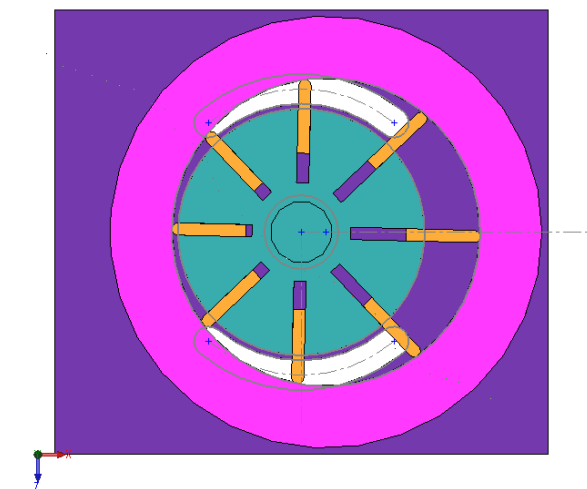

FIGURE 15

FIGURE 16

Compound Pressure Relief Valve

A compound pressure relief valve is a device used to limit pressure in a hydraulic system. Reference [1] depicts a typical valve of this type. The valve consists of a needle valve that variably dumps flow from a pressurized fluid channel to a low-pressure reservoir when its integral piston moves the valve to the opening position. The piston movement is controlled by a light spring and by the pressure balance on either side. The pressure on the piston tending to close the relief valve is controlled by a smaller spring operated pressure relief valve, hence the name compound referring to the fact that one pressure relief valve controls the action of another.

The compound pressure relief valve is another example of a mixed system. Both the mechanical operations of the valve components and the changes in the fluid pathways need to be visualized to understand its operation. A 3-D CAD system can easily meet both these needs. Using the CAD system's ability to extract a solid body from a cavity the entire flow path can be easily obtained once the solid model for the valve is completed. This cavity solid can be used for performing additional analysis for example a CFD analysis illustrating the flow parameters under varying operating regimes. There is an additional tool that can be used to make the 3-D CAD model available to the student called an eDrawing. An eDrawing does not allow a student to add to or modify a solid model in any way. But it does allow a student to view, section, markup and measure a 3-D solid model. Both the 3-D CAD system's use and the use of a subsequent eDrawing will now be explained.

Figure 17 shows how a 3-D CAD assembly model might represent a complex mechanism like a compound pressure relief valve. The source of data for this model was several figures in a hydraulics textbook; the actual part did not have to be in hand. The model has fifteen components in it of which eleven are unique. It took about two hours to construct in this way. As a result the dimensions for some of the critical passageways are not known. Determining the required dimensions, the sizing of springs and the diameter of critical passages would make excellent exercises or even a project. Figure 18 shows the component tree and update icons as well as the configuration tree. The update icons appear when one part controls the dimensions of another part in an assembly. The configuration tree shows that there are three configurations of the assembly, one showing the actual valve in a static condition and two showing the fluid cavity in both the valve closed and the valve open conditions. Note that the part representing the fluid cavity is shown ghosted. This indicates that in the view shown it is hidden, but not inactive. Should one of the other configurations be activated all the parts would be ghosted and the cavity would be shown in it normal colors. In this way parts can easily be made to "disappear" in order to allow the viewing of components behind them. Also note in the configuration tree that exploded views are created and activated as a sub tree of a particular configuration. Exploded views are used to show the separated individual parts with positions relative to their assembled locations.

A 3-D CAD system can therefore be used to create visually accurate models of real parts that can have a multiplicity of uses in a short time. These models can be

reused and stored in a much smaller space than a physical model would require.

In addition to classroom displays, there is a means by which a 3-D CAD model can be made available for the student to possess and interact with outside the classroom. It is called an eDrawing.
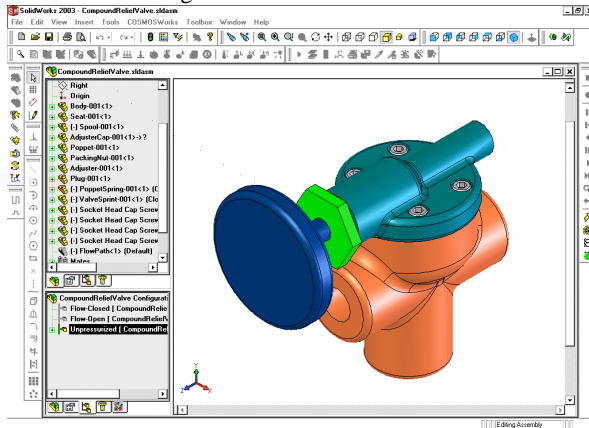
FIGURE 17

FIGURE 18

An eDrawing consists of only the fixed geometry data from a solid model. It is nothing more than the surfaces used to stitch together a solid model in the CAD software. An eDrawing also carries with it the capability to display, zoom, rotate, pan and section a solid body. With an assembly, an eDrawing also allows repositioning of the individual components in order to view the inside of a complex or closed part. Figure 19 shows the entire eDrawing interface,

menus, toolbars, configuration tabs, markup and measurement tools and comment area. eDrawings were originally conceived to allow transmission of engineering data outside of the originating department or company to other departments or companies without the recipient having to obtain the originating software to view the data.
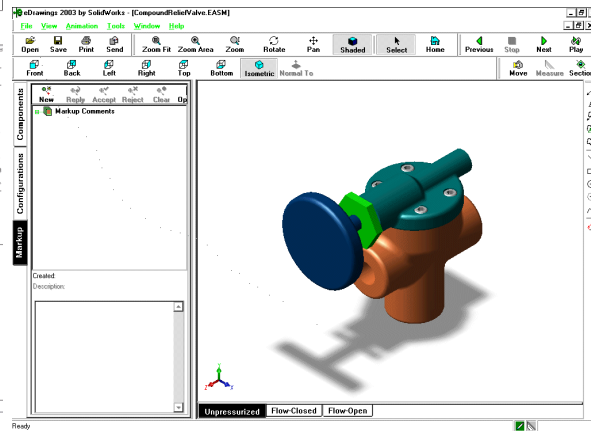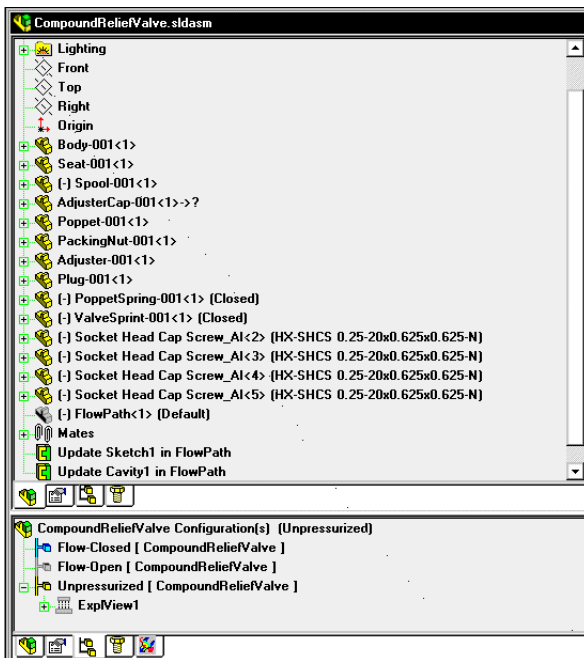

FIGURE 19

We will now walk through a scenario where an eDrawing might be used in a homework or project setting. Figure 19 shows and isometric view of the compound pressure relief valve. The eDrawing consists of the same configurations that were in the assembly model that produced it, namely the assembled valve and two configurations showing the valve in the closed and open conditions. The means of controlling the display of each of these configurations is shown in Figure 20. Simply clicking on the tabs displays the configuration and highlights the tab. Each configuration can be marked up, that is, annotations specific to the eDrawing can be added both in the graphics display area and in a separate text only window. Means for marking in the graphics window are shown in Figure 21 and means for controlling the status of a markup are shown in Figure 22. A marking is associated with the person making it via labeling in the markup tree. Figure 24 shows how a student might enter a response to a problem posed.
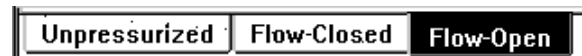

FIGURE 20

The instructor would therefore create an eDrawing of the compound relief valve assembly and suitably annotate it with information necessary to the homework or project like descriptions of the various components or instructions on what needs to be calculated. In this case the instructor labeled the various segments of the fluid passageways that controlled the pressure behind the spool valve. In the first note the instructor requested the pressures to be calculated along the flow path. The student responded with a markup

attached in an indented fashion to the instructor's markup. The markup would be returned to the instructor via email as a file separate from the eDrawing that the instructor could load back in to review each student's work.
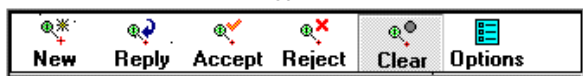

FIGURE 21

FIGURE 22

Once in the student's possession, students would be able to view each configuration as has been mentioned. For example the student could disassemble the valve as in Figure to see how it was constructed. Further the two views of the flow path that might be useful in understanding the functioning of the valve could be easily displayed using the section tool (see Figure 26 and Figure 27). By quickly activating these two views with the configuration tabs the effect of the movement of the spool valve on the fluid passageways can be seen. The diameter and length of each fluid passageway can be measured from the eDrawing itself. These views were created by using the section tool in Figure 23 and choosing the YZ plane as the section plane.

FIGURE 23

Because of the measurement capability the instructor need not include dimensions on the figure, instead requiring the student to perform the actual measuring. This provides a more holistic and practical experience. In addition, by not including dimensions the model can be varied from time to time if it is desired to change the answers or explore a number of different configurations for the valve.
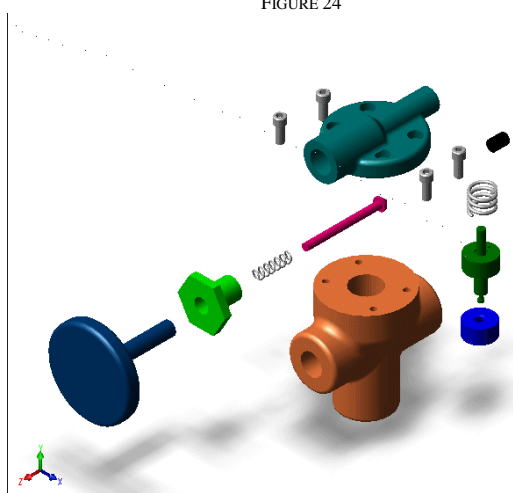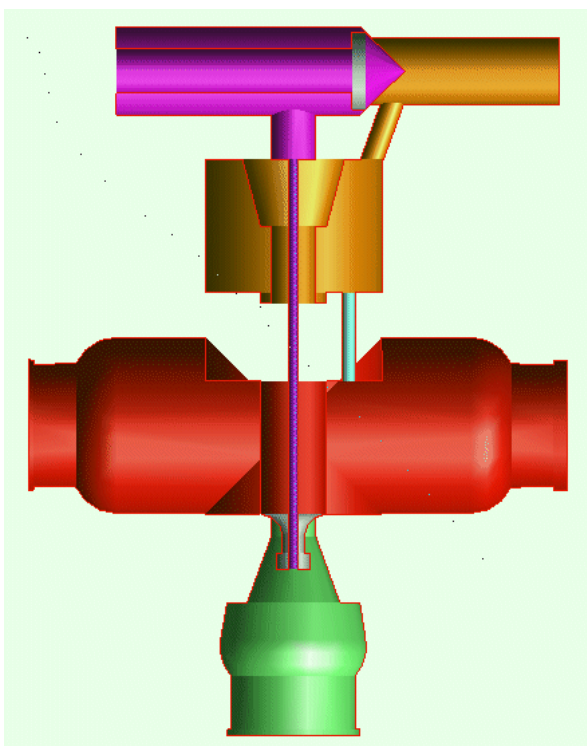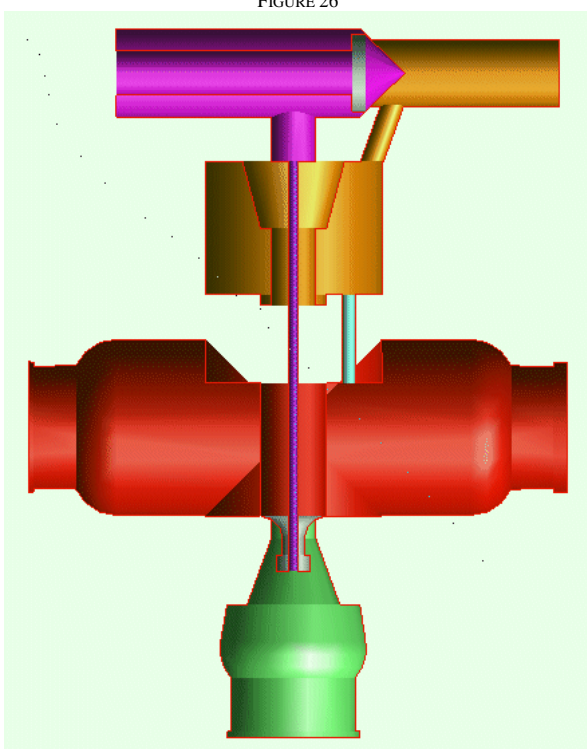

FIGURE 24

FIGURE 25

FIGURE 26

FIGURE 27

SOFTWARE

The CAD software used for demonstration purposes throughout this paper was SolidWorks 2003. eDrawings Professional was used to create the distributable 3-D models with the markup and measure capabilities. SolidWorks is a mid-range commercial CAD product with an installed userbase of approximately 200,000 users at the time of writing. EDrawings Professional is an addin for SolidWorks and AutoCAD that allows the distribution of files that can be viewed with free viewing software or that can be viewed via a self contained viewer. eDrawings is freeware, but it will only run on a Windows operating system. Windows 98 through XP will successfully display an eDrawing file.

PRESENTATION TOOLS

The projection of computer generated graphics requires some sort of device to project the image onto a suitable screen. Many modern classrooms are equipped for projection onto portable or built-in screens. For projection of CAD models a minimum resolution of 800x600 pixels should be sufficient. 1024x768 or greater would be even better especially if CAD models with text are to be projected. The models described in this paper can be viewed in a classroom setting using a computer projection system. Flat-panel displays coupled with overhead projectors are marginally capable of adequate resolution and brightness for satisfactory viewing in a dimmed room. Dedicated projection systems with bright, higher resolution capability are to be preferred.

Individual students can view eDrawing files on stand-alone PCs or via the internet. Making eDrawing files available to students via the internet or portable media, allows the students to manipulate and view the models at their own pace, while allowing the instructor to easily update course materials without having to make multiple copies on disks, CDs or other media.

Printed copies of 3-D models are inherently inferior to interactive software files. It may be helpful to students to have a printed copy of one or two views of a model as a reminder of the demonstration, perhaps with directional arrows added to indicate motion. In general though, distribution of printed text should be limited to introductory screens and user instructions.

3-D printing or rapid prototyping is another technique for improving student understanding of solid objects and mechanisms. [2] The computer models presented in this paper could be used to create physical models which could be examined and manipulated by students. The SolidWorks software will directly output STL files that are used by most 3-D printing systems.

TRAINING AND COST

A commercial version of SolidWorks was used to create the models used in this paper. However there is no difference in the functionality of the commercial version and the educational version save the fact that the educational version places a watermark on drawings when printed. Since drawings are not a part of the methods presented in this paper, that difference is of no consequence.

The cost of SolidWorks software to an educational institution is considerably less than the commercial version. An educational seat costs $300 per single seat, but is reduced to $150 per seat when more than 25 seats are purchased. The license must be renewed annually at a cost of $100 per seat per year which includes support. An educational seat of SolidWorks software comes bundled with eDrawings Professional, Animator, Toolbox, CosmosWorks and CosmosWorks with Motion. An educational seat of SolidWorks contains many more components than were used.

Ordinary eDrawings software is also available as a free add-in for users of both SolidWorks and AutoCad. When 3-D models are used by an instructor as a lecture tool, no training or software is required for students, but the students benefit from the enhanced information and visualization capabilities of the software.

For an instructor, there is an initial investment of time in learning the software and creating the instructional models to be used in the classroom. Once models of devices or mechanisms have been developed, they can be used many times with minimal additional effort for updating or improvement. This investment of time can be reduced by several instructors sharing the burden of model creation. In some institutions it may even be possible to make the creation of 3-D models part of a CAD instruction class.

For the software used in this paper a basic instruction class would require four days of the instructors time. The cost will be approximately $300 for the four days. However, many people prefer to learn the software on their own and there is no compelling reason to not learn the software this way, but the structured class is likely to give a more rounded training in the end.

The cost benefits of using a software based approach to 3-D learning aids is as follows: First, the high cost of purchased or custom built models is eliminated. For the sake of argument we will assume that the compound relief valve model used in this paper was given to the school by a valve vendor. The school would then have to have its model shop or equivalent section the valve in such a way that it could illustrate some of the functionality of the valve. Based on past experience this might require 16 hours of shop time at $50/hour resulting in a departmental cost of $800 for this single model. For the $800 spent there is now a single model that must be replicated in every branch that the school has. This level of cost is one reason why more 3-D models of mechanical equipment are not seen in the classroom. Then there is the cost of warehousing and maintaining the models. This requires non-productive time from staff or instructors. Storage space in educational institutions is frequently at a premium. On the other hand the storage requirements for a CAD model are miniscule and the CAD model can be used and reused by the entire staff of a university or school.

It is also likely that an educational institution would want to find other applications for the software, like CAD instruction or other modeling applications in order to justify the cost of the purchasing and maintaining the software. In addition, the software bundled with SolidWorks includes Finite Element and integrated 3-D kinematic analysis. The use of these software packages for instructional purposes also shows promise.

Distributing eDrawing files to students is low-cost, since no special software is needed to view the eDrawing models. Students should be able to open and manipulate eDrawing files with minimal instruction, since the models are already constructed and the functions of the software are primarily limited to viewing.

SUMMARY

Interactive 3-D models can be developed to illustrate not only complex structures, but also the dynamic behavior of mechanisms and fluid flow patterns inside devices like pumps and valves. The resources required to create models for lecture or for distribution to students is minimal compared to the instructional value of the models as learning tools the current crop of 3-D CAD software brings the benefits of working models within the reach of the classroom.

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[1] Esposito, Anthony, Fluid Power with Applications, 6th ed., Prentice Hall, Upper Saddle River, NJ, 2003, pp. 273-299.

[2] Czapka, J.T., Moeinzadeh, M.H., and Leake, J.M.,"Application of Rapid Prototyping Technology to Improve Spatial Visualization", Proceedings of the 2002 American Society for Engineering Education Annual Conference, paper no. 1808