Abstract
One of the most difficult tasks for students and even practicing engineers is to visualize and understand how a mechanism or machine operates based on written descriptions and static illustrations. Historically, engineers have learned about machines by studying physical models and tinkering with real machines and referring to published catalogs of useful mechanisms. In recent years, this form of learning is disappearing for a variety of reasons, with the result that students graduate from mechanical engineering never having seen common machines and mechanisms like planetary gears, universal joints, common linkages, etc. This paper describes how multimedia mechanism animations and simulations can improve student understanding of common mechanisms and their applications.

Background
In the early days of engineering and engineering education, it was common for students and engineers to be exposed to physical models and samples of a wide variety of machines and mechanisms\(^1\). Mechanical engineers became familiar with many common mechanisms, and understood their operation. Furthermore, many early books cataloged useful mechanisms and their applications. For example, Hiscox’s *Mechanical Movements*\(^2\), published in 1904, contains illustrations and descriptions of 1800 mechanisms.

In the second half of the 20\(^{th}\) century, the focus in engineering education turned toward engineering science, and practical matters were de-emphasized. Since then, mechanical engineering education has focused on analysis of mechanisms, rather than synthesis or application. Few students today have seen let alone tinkered with real mechanisms or machines, and have little or no understanding of how they work or where they can be applied. Analysis does not provide this insight.

Few modern books contain descriptions and practical applications of common mechanisms. A notable exception is the *Mechanisms and Mechanical Devices Sourcebook* by Chironis\(^3\). It contains extensive descriptions and diagrams of useful mechanisms. However, it can be hard to visualize how these devices operate based on written descriptions and static diagrams.
Animations and Simulations of Mechanisms and Machines

Some of this important knowledge and understanding of common mechanisms and machines can be regained through the use of animations and interactive computer simulations. In many cases, the operation of a machine becomes instantly clear as soon as one sees it move. Furthermore, machines can be studied in great detail using interactive simulation and analysis packages. These simulations allow the machine to be started and stopped, the user’s viewpoint to be changed, and kinematic and dynamic data to be collected and analysed. These simulations permit students to study and understand the operation of many common mechanisms, and to develop a cognitive schema so that they can readily recall and apply these mechanisms to practical engineering design problems.

New CAD and mechanism simulation packages have simplified the creation of these virtual models to the point where it is feasible to create an entire library of mechanism models for educational use. These packages are typically easy to learn and use, and running an existing simulation model usually requires little knowledge of the software. Representative Windows-native CAD packages include Inventor, SolidWorks and Solid Edge. Leading packages for mechanism simulation and analysis include ADAMS, Dynamic Designer and VisualNastran 4D. These packages usually have attractive and affordable academic licensing programs, and are often already available on campus. For example, Solid Edge offers an unlimited academic site license for about $1500 per year, which includes permission for students to install the software on their own computers. Dynamic Designer software is free for academic use, and can be distributed to all academic Solid Edge users.

Courseware using mechanism simulation tools has appeared in recent years. Mechanism Design by Erdman, Sandor and Kota includes over 200 ADAMS mechanism animations and simulation models. Engineering Mechanics: Statics and Dynamics by Hibbeler, includes a CD-ROM with over 120 simulation models based on Working Model 2D from MSC Software.

To the author’s knowledge, no one has yet attempted to create a catalog of useful mechanisms including animations and simulation models.

Procedure for creating a mechanism simulation

This section outlines the generic procedure used to create mechanism animations and simulations using a midrange CAD package coupled with a mechanism simulation package. The author is most experienced with Solid Edge and Dynamic Designer, but the procedure would be similar with other tools.

Creating CAD models

Mechanisms can be initially modeled as assemblies of parts in most CAD packages. The simplest method to use is to create parametric, feature-based part models of the individual parts, and then to combine them into an assembly model. Most modern CAD packages position parts in an assembly using assembly relations or constraints. The most common of these are:
- **Planar mate.** This brings two specified planar surfaces into contact. They can also be offset a fixed distance, or be constrained to remain parallel.
- **Planar align.** This is similar to planar mate, only the selected surfaces are aligned with their surface normals pointing in the same direction.
- **Axial align.** This aligns the axes of two cylindrical features, such as a hole and a shaft.

Normally, three assembly relations are applied to fully constrain the relative motion of two parts in an assembly. For mechanisms, one or more degrees of freedom must exist between two parts. In this case, fewer relations are defined. For example, a revolute joint could be defined by an axial align and a planar mate or align, and a cylindrical joint could be defined using only an axial align.

CAD assembly models are used primarily to visualize the final assembly, to check for static interference, and to produce assembly drawings. In general, CAD assembly models don’t move.

**Turning CAD models into mechanism models**

Once a CAD assembly model is created, it is straightforward to extend this to a kinematic or dynamic model. Some CAD systems have this capability built in, and others use third-party software. The procedure below is based on Dynamic Designer, but other software would require similar steps.

1) **Specify units and gravity**
   The first step is to specify the units, and to define the gravitational field. Gravitational acceleration can be turned on and off, and its direction and magnitude can be specified.

2) **Specify ground and moving parts**
   A mechanism is composed of parts that are grounded, and parts that move. The grounded and moving parts can be specified or inferred automatically.

3) **Define mass properties**
   Dynamic modeling and simulation requires specification of the mass properties of the parts. These can be specified manually, or calculated automatically from the part geometry and material properties.

4) **Apply constraints (joints and motions)**
   Once the moving and grounded parts are defined, their relative motion must be constrained by connecting them with joints and specifying motions on remaining degrees of freedom. Common joint types include:

   - Revolute
   - Cylindrical
   - Spherical
   - Translational
   - Planar
   - Universal
• Helical

Some packages permit more complex constraints like contact to be defined as well.

For a kinematic analysis, motions are specified for the remaining degrees of freedom. Motion is specified by defining a rotational or translational motion along a degree of freedom of a joint. The motion can be constant, harmonic, or some other function, and can be specified as a function of displacement, velocity or acceleration. For example, if a constant angular velocity is specified for the revolute joint of a motor-driven input link of a four-bar linkage, then the motion of the entire linkage can be determined.

If the degrees of freedom are not fully constrained by joints and defined motions, then the mechanism motion will be determined by the equations of motion based on the initial conditions. For example, a four-bar linkage with all joints allowed to rotate freely will move under the influence of gravitational and other applied forces.

5) Apply forces
The dynamic motion of a mechanism is governed by applied forces. Typical force elements are springs and dampers, but more general action/reaction forces can be defined between pairs of parts in the mechanism. Externally applied forces and torques can also be defined.

Simulate mechanism model
Once the model is fully defined in the preceding steps, the resulting motion can be simulated by numerically solving the full equations of motion. Most motion simulation packages include robust numerical solvers, so little knowledge of the numerical details is required. The user might specify the number of simulation steps, or the duration. Running the simulation requires no more than clicking a “Simulate” button.

While the simulation is running, kinematic and dynamic data is collected for later analysis. The data collected typically includes:

• Position, velocity, acceleration of centre of mass
• Linear and angular velocity and acceleration of body
• Kinetic and potential energy
• Bryant angles, Euler angles, Yaw/pitch/roll, Rodriquez parameters
• Joint linear and angular position, velocity and acceleration
• Joint reaction forces and moments

Any of these parameters can be plotted as a function of time, and the data can be exported to a spreadsheet for further analysis if desired.

The effect of changes to the system can be studied by modifying any of the geometric, kinematic and dynamic parameters and re-running the simulation. Changes that could be explored include:
- Change link dimensions
- Change mass properties
- Change spring or damper rates
- Change applied force magnitudes and directions

Some packages like ADAMS permit systematic system optimization by varying several parameters simultaneously.

Create animation files
Most motion analysis packages allow the simulation results to be saved as an animation in common formats, including AVI and VRML2. AVI animations are simply movies, and are non-interactive. VRML2 animations permit the viewpoint to be changed, so that motion can be viewed from different directions. Animations do not permit detailed study, but also do not require the original mechanism simulation software.

Save and distribute dynamic models
Once a simulation model is created, it can be saved and distributed to students. Simulation studies using these models require the corresponding mechanism analysis software to be installed. For example, ADAMS must be installed to open and interact with ADAMS simulation models.

Export simulation data for further analysis
It is often easiest to create simulation models using midrange CAD and mechanism simulation packages like Solid Edge and Dynamic Designer, but these have limitations. For more advanced analysis, Dynamic Designer simulation data can be exported to ADAMS. Also, data can be exported for FEA analysis.

Example – four-bar linkage
This section presents an example of how a four-bar linkage motion model can be created using Solid Edge and Dynamic Designer.

Model the parts
The process for creating solid models of parts is fairly standard with modern parametric CAD packages like Solid Edge. Usually, one starts by sketching a rough profile of the part and extruding or revolving it to create a 3D base part. The base shape is then refined by progressively adding and removing material using a set of feature operations like “extrude”, “cutout”, etc. Dimensions can be modified at any time, and the model will update.

To model a four-bar linkage, we need two grounded brackets, an input link, a coupler and an output link. Each can be modeled as an extruded profile in just a few minutes. For example, the coupler link can be modeled by extruding a profile, then cutting out two holes as shown in Figure 1.
Assemble parts using assembly relations

Once the necessary parts have been created, they are brought together into an assembly. This is done by first defining a base part, and then adding other parts to it. Each part is placed into the assembly by defining a set of assembly relations. For the four-bar linkage, we can place one ground bracket as the base, then position the second ground bracket relative to the first with planar aligns. Other links are added sequentially until the linkage is complete as shown in Figure 2. The joints must permit one rotational degree of freedom, so only two relations are applied to connect the links together: a planar mate and an axial align. At this point, if we modify the link lengths, the linkage will reconfigure to satisfy the joint alignment constraints. For example, Figure 3 shows the result of increasing the length of the input link.
Figure 2. Assembly model of 4-bar linkage in Solid Edge.
Convert assembly model into mechanism

To convert the assembly into a mechanism, it is necessary to define the kinematic and dynamic parameters. Dynamic Designer assists the user with Wizards, and can infer the joint types and moving links from the assembly relations. Figure 4 shows the mechanism model generated by Dynamic Designer from a Solid Edge assembly model. Note that Dynamic Designer works inside Solid Edge rather than as a separate application.
Figure 4. Dynamic Designer mechanism model.

**Define input motion**

To simulate an input link driven by a motor, we can apply a constant angular velocity about the axis of the input joint using a dialog box as shown in Figure 5.
Simulate and analyse data

The mechanism is now ready for simulation. We accept the default simulation duration and step size, and click the “simulate” button.

We can now plot any data of interest. For example, we can plot the output link angle as a function of time, and the magnitude of the reaction force between the input and the coupler. Plots can be viewed within Dynamic Designer, or data can be exported to Excel or other analysis software for further processing.

Create and distribute animations

Once the simulation is complete, we can replay the motion without running the simulation again. We can also save the simulated motion as an animation file in AVI or VRML2 format. These animations can be embedded into a multimedia document, distributed on CD-ROM, or posted on a website. Figure 6 shows a screenshot of the resulting AVI animation, including the selected data plots. Figure 7 shows the corresponding VRML2 model displayed using the Cortona VRML client. In addition to the usual animation playback controls, the VRML2 model allows the viewpoint to be interactively changed. Unfortunately, display results seem to vary unpredictably depending on the viewer used. The Cortona client appears to be one of the only VRML viewers that is still actively supported.

If this were a multimedia document, these animations could be played directly from this page. Readers wishing to see the live animations are encouraged to contact the author.
Figure 6. Screenshot of animation in Microsoft Media Player.
Conclusions

Animations and interactive simulations of mechanisms can provide insight and understanding previously achievable only through physical experimentation and hands-on experience. Current CAD and mechanism simulation software makes it easy to create mechanism simulations, and hopefully in the future multimedia mechanism catalogs will be available to allow students to gain rich experience with many common mechanisms, and to easily find suitable mechanisms for specific design applications.

References

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