

Interactive 3D Visualization Of Rigid Body Systems

Zoltán Konyha*

Krešimir Matković†

Helwig Hauser‡

VRVis Research Center, Austria

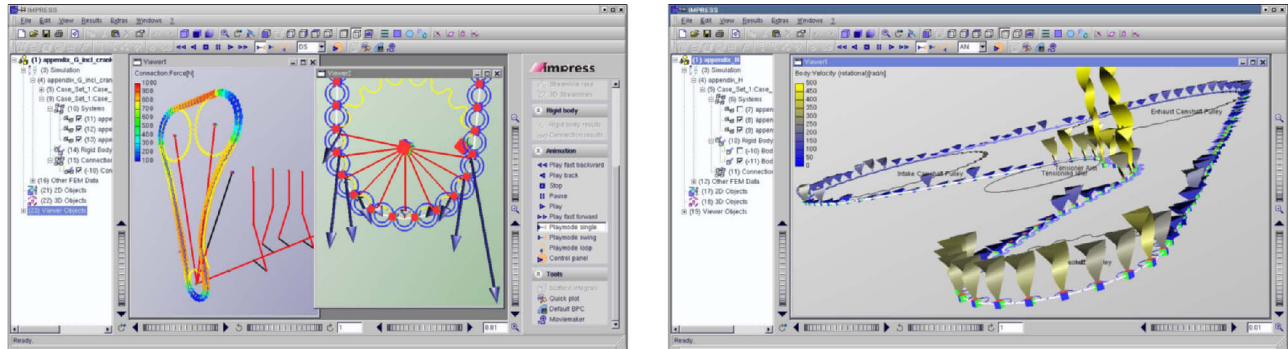


Figure 1: Interactive 3D visualization of chain and belt drives integrated into Impress.

Abstract

Simulation of rigid body dynamics has been an field of active research for quite some time. However, the presentation of simulation results has received far less attention so far. We present an interactive and intuitive 3D visualization framework for rigid body simulation data. We introduce various glyphs representing vector attributes such as force and velocity as well as angular attributes including angular velocity and torque.

We have integrated our visualization method into an application developed at one of the leading companies in automotive engine design and simulation. We apply our principles to visualization of chain and belt driven timing drives in engines.

CR Categories: I.3.8 [Computing Methodologies]: Computer Graphics—Applications; I.6.6 [Computing Methodologies]: Simulation And Modeling—Simulation Output Analysis

Keywords: rigid body dynamics, rigid body simulation, glyph based visualization, iconic visualization, automotive industry

1 Introduction

When hearing “rigid body visualization” most of the people in the computer graphics community think of the systems for describing, simulating, and animating/visualizing rigid body systems, like

*Konyha@VRVis.at

†Matkovic@VRVis.at

‡Hauser@VRVis.at

skeletons used for human body animations, or similar application [Sauer and Schömer 1998; Park and Fussell 1997]. Actually, computer graphics is not the only field encompassing rigid bodies. Mechanical engineers have dealt with them on a daily basis for a quite some time. Simulation tools exist which simulate complex rigid body systems, used by mechanical engineers, which overcome the tools used in computer graphics. The main goals of the two systems are different. On the one hand, computer graphics people dealing with rigid body simulation are primarily interested in creating “good-looking” animations with preferably real time and interactive simulation. On the other hand the main goal of mechanical engineers is to make the simulation as correct as possible which makes the simulation more complex. Our goal is to develop a visualization front-end for such complex simulation tools. The users of these system are not animators and designers, but engineers working with it on a daily basis. The data set we visualize is produced by rigid body simulation used in modern engine design.

First we focus on visualizing chain drive and belt drive simulation results. These systems are composed of many individual bodies which makes them difficult to evaluate using conventional methods. Visualization should help in the exploration and analysis (primarily) and in presentation of the simulation data. Up to now, analysis was done using a large amount of 2D charts and numbers. Such an analysis is very time-consuming and complicated. Visualization techniques proposed in this paper make it easier to interpret simulation results. The user can explore the data interactively and spot potential problems much easier than without visualization. Furthermore, some of the simulation results, like 3D vectors and relative positions in 3D space, are nearly impossible to imagine without 3D visualization.

This paper describes rigid body simulation first, since some of the readers may not be familiar with its applications in the automotive industry. We will then proceed with the description of the visualization system. Since the whole visualization is based on various glyphs [Post et al. 1995; van Walsum et al. 1996; de Leeuw and van Wijk 1993], the glyphs used will be introduced. Finally, the commercial application developed in cooperation with AVL [AVL n. d.] is presented. As far as we know this paper describes the glyph based visualization of rigid body simulation data for the first time.

IEEE Visualization 2003,
October 19-24, 2003, Seattle, Washington, USA
0-7803-8120-3/03/\$17.00 ©2003 IEEE

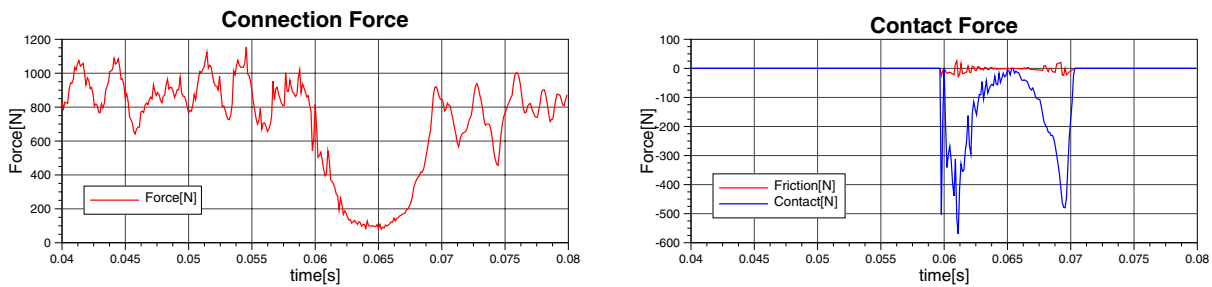


Figure 2: 2D charts showing (a) forces between two neighboring chain links and (b) forces between a chain link and sprocket.

2 Rigid Body Simulation

With increasing computational power simulation can be processed faster and with more precision than ever before. Rigid body dynamics is an established model of real world dynamics that allows reasonably accurate simulation of certain systems at an affordable computational price. In rigid body simulation [Baraff 1989; Mirtich and Canny 1995; Mirtich and Canny 1996] real world objects are modelled by physically ideal rigid bodies that can have 6 degrees of freedom (translation and rotation along all three major axes), but cannot be deformed. The bodies are connected by connection elements that are basically springs with dampers. Bodies can also come into contact occasionally by colliding with each other.

Rigid body simulation is extensively used in industrial simulation including automotive industry [Hoffman and Dowling 1999], aircraft and ship design. Engineers are interested in simulation since it is much faster and cheaper than producing a physical prototype. Prototype production and testing is still – and will be – common in engine production. However, simulation can reduce the number of prototype cycles and thereby improve development speed and cut down costs. The simulation data in our case comes from *AVL Tycon*, a rigid body based simulator developed at AVL [AVL n. d.] for the design of timing drives in engines. We focus on chain and belt drives in this paper. In simulation both chain and belt drives are handled in the same way. In chain drives each chain link is a rigid body interconnected via stiff springs that model the pins. Belt drives are simulated by dividing the belt into several rigid sections. Let us examine a typical chain drive simulation first.

A typical chain drive has 100-200 chain links. The simulator computes data for approximately 5000 time steps. For each time step and rigid body, e.g chain link a set of approximately 20 attributes is computed. The attributes include:

- displacement and orientation of bodies
- translational and angular velocity of bodies
- translational and angular acceleration of bodies
- forces and torques in connections between bodies
- relative displacement and relative velocity between endpoints of the connections

It is clear that the amount of data produced for such a relatively simple system is huge and not easy to analyze. So far the simulation results have been presented in 2D graphs that provide vague resemblance to the actual 3D models. Figure 2 shows two such graphs displaying connection forces between two neighboring chain links and contact forces between the chain link and the sprockets. Note that these two charts represent one link only, and that there are about 200 such charts describing only one attribute, e.g. force between chain links.

Our goal is to develop a more intuitive 3D visualization system for rigid body simulation data which makes the analysis faster and

enables the user to explore the data in ways not possible in 2D charting.

3 Rigid Body Simulation and Visualization

The overwhelming amount of data and 2D charts produced by the simulation is hardly manageable even for an experienced user. Therefore visualization should be used to assist the user in exploration, analysis and presentation of the data. Since the primary users of such visualization tool are engineers, the main goal is to support data exploration and analysis. Visualization supports data exploration in numerous ways.

The next section describes the motivation for developing an interactive 3D visualization framework for rigid body simulation data.

3.1 Motivation for Interactive 3D Visualization

An experienced engineer can certainly gather a lot of information from 2D charts, but having the visualization feedback can speed up the process significantly. It is difficult and often even impossible to imagine complex 3D geometry from numerical data only. For example, if there is a sprocket with its radius and position given in 3D space on the one hand; and a chain link with its geometry, position and orientation on the other, it is practically impossible to predict if the chain link actually touches or even intersects the sprocket. Rather all 3D vector quantities, like contact point positions or forces between sprockets and links, accelerations, etc. are difficult to imagine based on 3D coordinates only.

Furthermore, if the user wishes to examine more attributes simultaneously, the 3D visualization offers many possibilities. Interactive exploration where the user can navigate through, adjust or toggle parameters is simply not possible using conventional non-interactive means.

The behavior of the chain drive is of interest to engineers only when the chain drive is in motion. The 2D charts cannot depict the motion. On the contrary, interactive visualization can display the chain in motion and thereby enrich the static data. This feature is especially valuable to users who want to have an overview of the dynamic behavior.

If the user wants to explore a particular space in the system, e.g where chain leaves the sprocket, they can simply zoom in and explore parameters for all chain links passing by. Doing the same without interactive visualization would require scanning through numerous charts, looking for each chain link in turn. If the user is interested in more than one attribute at the same time the process can become frustrating. It is clear that visualization can improve the presentation of rigid body simulation results.

The simulation models of chain and belt drives in *Tycon* are identical. Identical attributes are computed thus the same visualization

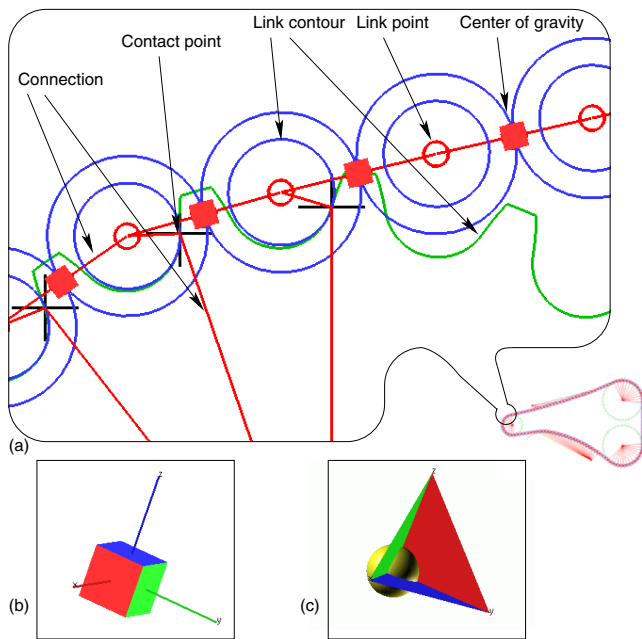


Figure 3: (a) Model of a chain drive. Overview and zoom of a part showing elements. (b) and (c) options for drawing center of gravity and local coordinate system.

methods can be applied to both drive types. In order to visualize attributes we use various glyphs. In the following section we describe the glyphs used in our visualization solution.

4 Glyphs for Rigid Body Visualization

In order to represent the rigid body system itself and related attributes various glyphs are required. The following sections introduce the glyphs we propose for visualization of bodies and connections in rigid body systems. The glyphs representing vector attributes (forces, velocities) and angular attributes are also described.

All glyphs described can depict multiple attributes simultaneously. However, correlation of attributes in rigid body simulation is quite natural. Therefore we generally map only one attribute to one glyph for simplicity.

4.1 Model of Rigid Body System

Rigid body systems in physics consist of *rigid bodies* and – generally elastic – *connections*. The bodies have a *center of gravity* and any number of *link points* defined in the body's local coordinate system. The center of gravity is by default represented by a cube which indicates the orientation of the body. The orientation can be clarified further by drawing the bodies local coordinate system as shown in Figure 3 (b) and (c). This is especially necessary when the user decides to use a sphere glyph to represent the center of gravity.

Connections run between link points of two bodies. Each link point has a *contour* assigned which is used in the simulator to calculate contact points between bodies. This modelling paradigm implies that a sprocket for example is modelled as a single rigid body with one link point at its center. The contour of this link point (shown in green in Figure 3) a) is the actual shape of the sprocket. Similarly, each chain link has link points at both of its pins that have circular contours, shown in blue. The smaller circle is the surface

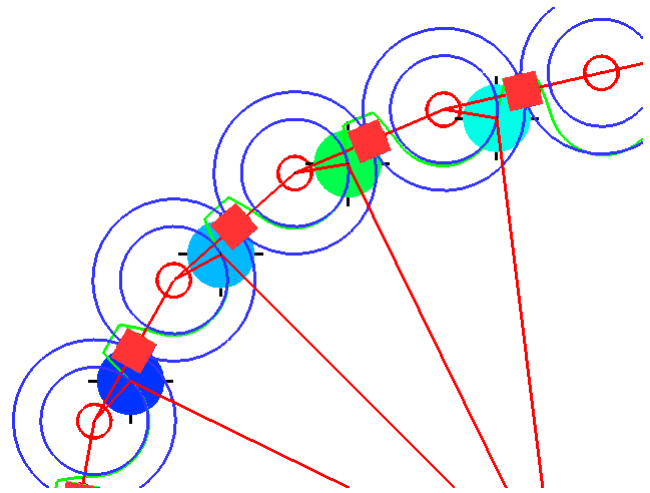


Figure 4: Color coded disks visualizing the magnitude of contact forces between a sprocket and chain links. The disks are positioned at the contact points.

that comes into contact with the sprocket while the larger circle is the outer surface of the link sliding on guides.

4.2 Colored disks

A very simple glyph that was found to be especially useful in visualizing magnitude of forces is a simple color coded disk shown in Figure 4. It has proved to be a quick way of locating the areas of extreme forces – something engineers perform very often as a first step when investigating a chain drive. The color is mapped to the visualized attribute. The sizes of all disks are the same. However, the user can specify the diameter of the disks to suit various model sizes.

4.3 Arrows

Probably the most straightforward way to visualize vector quantities is using arrows. Force, translational velocity and acceleration are often depicted using arrows in physics, thus it comes natural to use them in our visualization framework, too. The direction and the magnitude of the visualized attribute are indicated by the direction and length of the arrow. The starting point of the arrow identifies the point in space where the force acts.

In our implementation we offer 4 drawing styles of arrow glyphs. This allows the user to visualize various vector attributes simultaneously without confusing them. As shown in Figure 6 we offer flat head and cross head arrows, along with 3D cone head and pyramid-shaped ones. However, in 3D visualization only (c) and (d) should be used. (a) and (b) are more suited to 2D scenarios.

It is possible to visualize the real 3D vector or just its components in the body's local coordinate system. This offers the chance of visualizing only the normal component of the velocity of chain links for example as seen in Figure 12.

In addition, it is also possible to show any component along *any* axis of the local coordinate system. The advantage of this becomes obvious when one tries to display tangential velocity of chain links. The arrows would "pile up", occlude each other and render the image illegible as shown in Figure 5 (a). Our solution allows the user to display the tangential component *normal* to the chain itself as shown in Figure 5 (b). By doing so they have a good presentation of the magnitude, while the direction is known to be tangential

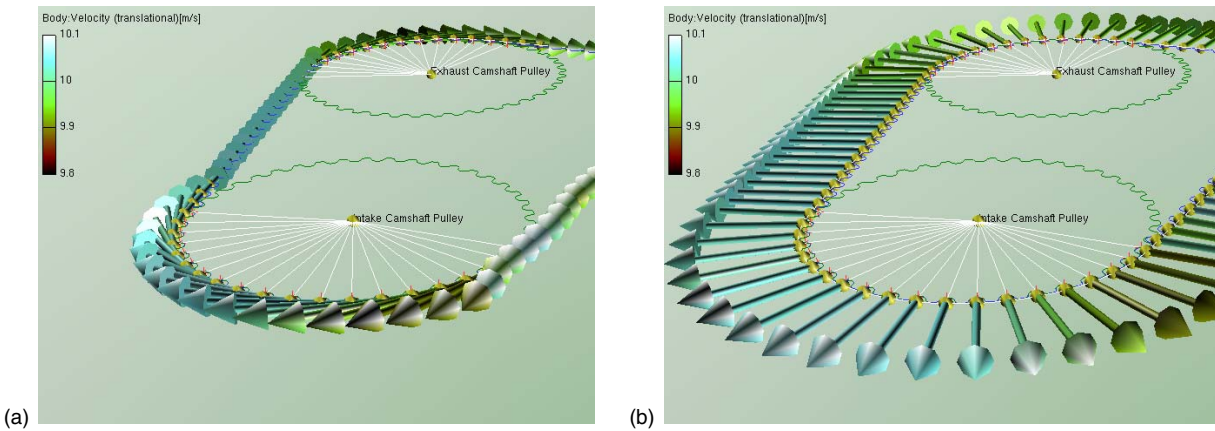


Figure 5: Tangential velocities of belt drive slices. (a) Arrows occlude each other when drawn in their real direction. (b) Occlusion reduced by displaying tangential velocity normal to the real direction.

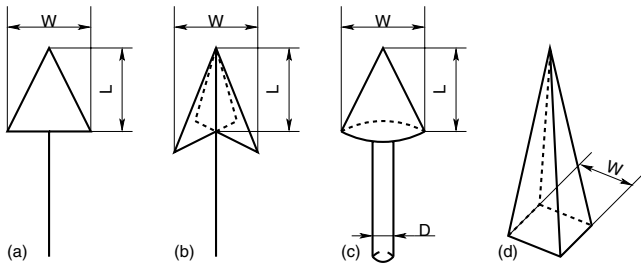


Figure 6: Models of (a) flat head, (b) cross head, (c) cone head and (d) pyramid-shaped arrows. Customizable parameters (width and length of arrow head, diameter of shaft) are also indicated.

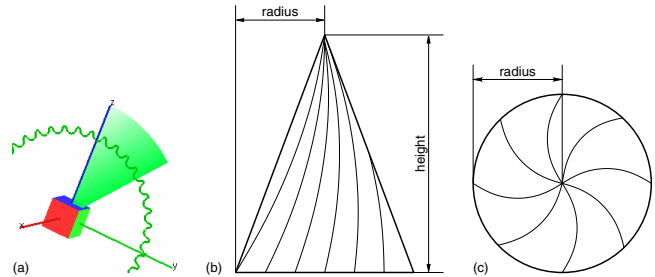


Figure 7: Glyphs for angular attributes: (a) sector glyph on one body visualizing angular velocity, (b), (c) sketch of a spiral mapped on the side of a cone. (b) side view, (c) top view.

a priori. It must be mentioned that such a rendering may be open for misinterpretation to novice users. However, experienced mechanical engineers are used to such representations because it has been a common method of displaying chain forces in figures. An example is shown in [Niemann and Winter 1986].

The arrow glyph can visualize the assigned attribute by changing its length or by full 3D scaling. Although the latter introduces the "visualization lie" [Tuft 1986] effect because of the nonlinear change in surface, in some scenarios it still turns out to be preferred by users because it makes extremely large attributes more noticeable.

It is also possible to apply optional color coding to the arrows to reflect their magnitude. Users may be interested in the actual value a glyph represents, thus annotations can be attached to the arrow glyphs as shown in Figure 12.

4.4 Sectors

Visualizing angular velocity and acceleration is somewhat more challenging. In computer graphics orientation and angular velocity are generally described by the axis of rotation (a vector) and the angle of rotation (a scalar) around that axis. To the contrary, the simulator we interface to represents rotation with Euler angles and the engineers expect to see these three angles in visualization, too.

Coming up with a glyph that visualizes 3 rotational degrees of freedom in an intuitive and unambiguous way is not easy. Therefore we have opted to visualize only one component of the angular

velocity in the body's local coordinate system with one glyph. Additional glyphs of the same type can be instantiated to visualize further components.

One glyph that has proven to be intuitive is a sector. The sector's center is at the center of gravity of the body. The plane is rotated normal to the axis of rotation, thereby directly indicating it. The magnitude is visualized by the angle of the sector. The direction of the rotation (clockwise vs. counter-clockwise) is made clear by changing the transparency along the arc. This immediately defines the direction of the movement since it gives the impression of an arm leaving traces during sweeping over the arc. Figure 7 (a) shows a single body (the center of gravity of a sprocket) and a sector glyph that indicates its angular velocity.

The radius and the angle mapped to the maximum of the attribute can be specified by the user. As with arrows, the user is given the option to use color coding as a further means of stressing magnitude.

4.5 Spirals

Although the sectors mentioned above are suitable they have a major drawback. They are 2D objects, and when viewed under very small angles they are difficult to interpret. In the extreme case they appear as thin lines on the screen completely unable to convey anything other than perhaps the color.

To overcome this problem we have developed a glyph that is

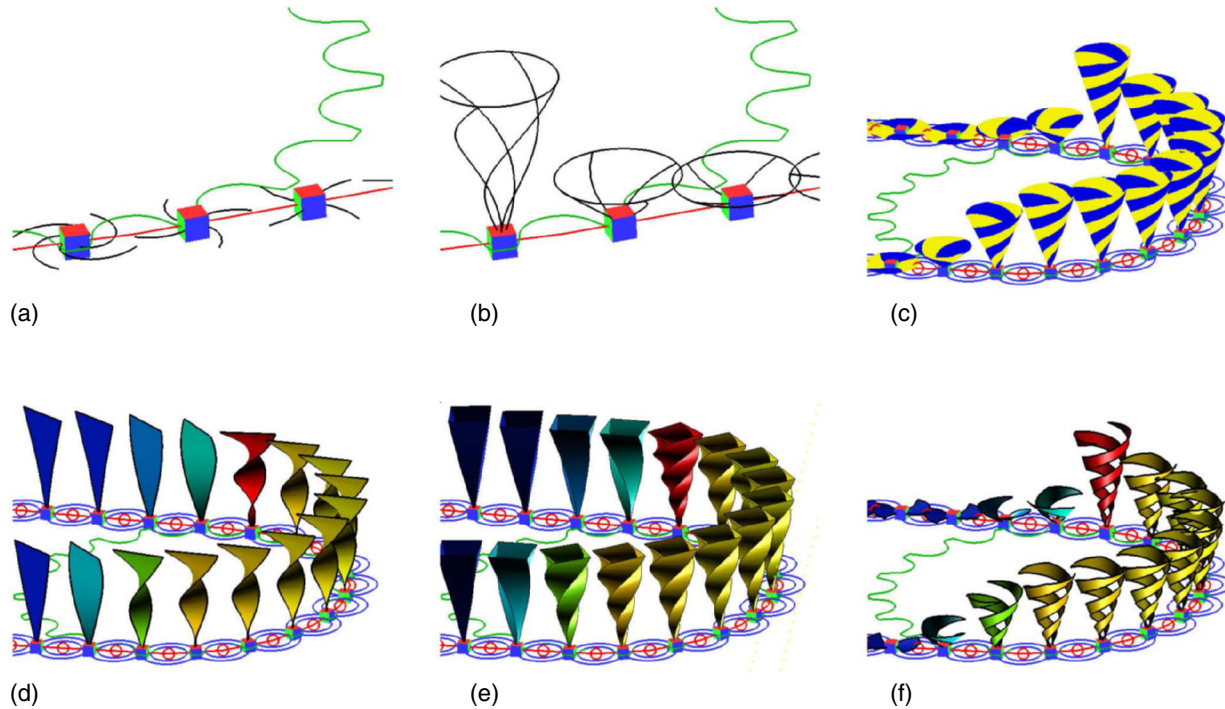


Figure 8: Rendering styles for spirals: (a) wireframe, (b) wireframe with circle, (c) filled, (d) helix, (e) pyramid, (f) ribbon.

capable of visualizing angular attributes reliably no matter where from it is viewed. The basic idea is simple: take a star-shaped glyph with a few arms and transform it into a spiral by twisting its center. The larger the attribute the more the spiral is twisted. This object is still 2D, therefore it is prone to similar visibility problems as the sectors. Now map these lines onto the surface of a cone and make the cone's height also a function of the attribute being visualized. This results in a 3D glyph shown in Figure 7 (b) and (c) which can visualize angular quantities reliably regardless of the viewing angle. When viewed from the top or bottom the twisted spiral arms are easily interpreted. When seen from the side the spiral arms are not as clearly visible as from the top. However, in this case the height of the cone provides additional clues to the viewer.

The cone is rotated so that its axis coincides with the axis of rotation. The direction of the rotation is made clear by twisting the spiral clockwise or counter clockwise, respectively.

We again offer many rendering options to facilitate simultaneous visualization of various attributes and allow the user to choose whichever style they prefer. The user can change (1) the maximum twist angle (2) radius of the disk at the base of the cone (3) number of spiral arms (4) scaling factor of the cone's height. There are 6 rendering styles as shown in Figure 8: wireframe (with or without the circle at the base of the cone), filled, helix, pyramid and ribbon. The cones can be made the same height as seen in (d) and (e) in Figure 8. Color coding and annotations are again optional.

A valuable feature is the optional animation (rotation) of the spirals. The speed and direction of the rotation reflects the attribute visualized. This has proven to be very popular with users because it indicates rotation in the most natural way.

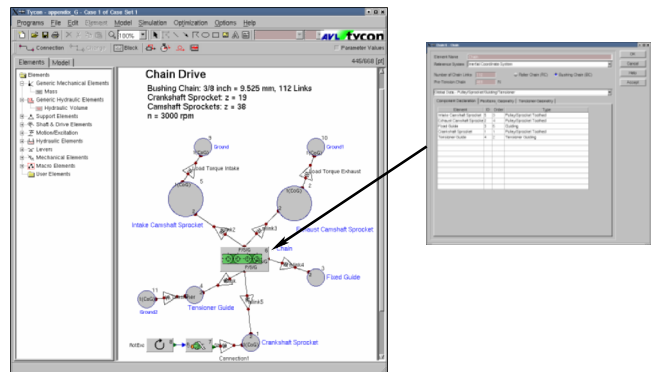


Figure 9: Block model of a chain drive in Tycon with the property dialog of one element.

5 The Application

AVL offers a full range of software for simulation in the automotive industry. The AVL Workspace is a common user-friendly framework for simulation tools including, amongst others, *Tycon* for valve train and timing drive dynamics that is based on rigid body dynamics. It also includes a common visualization tool called *Impress* which can process output from all simulation modules. The rigid body visualization capabilities of Impress are based on the principles described in this paper. We will now guide the reader through the typical workflow of an engineer working with AVL Workspace. We will put more emphasis on detailing the process of evaluating the simulation results.

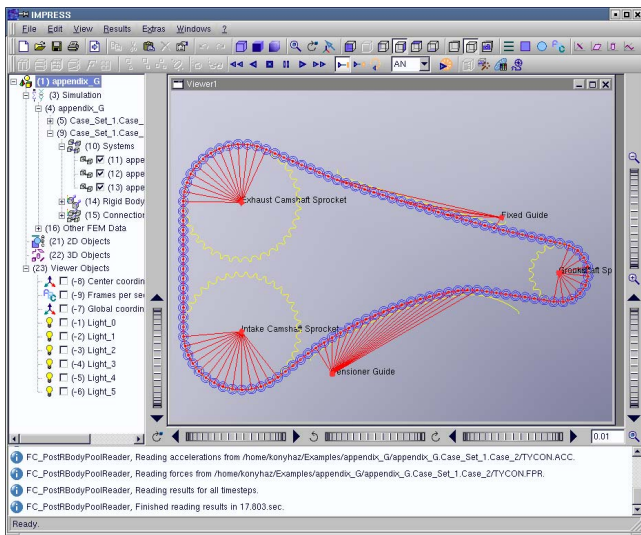


Figure 10: Main window of Impress.

5.1 Model Generation

Tycon enables the user to build a 2D block model of the timing drive. The Tycon user interface is shown in Figure 9. There is a tree view of elements that can be inserted into the workspace. Properties such as name, mass, initial position and link points can be specified in popup dialogs for each element. There are specialized tools to assist the definition of contours of profiled elements, e.g sprockets. Connections are created by clicking the appropriate link points on the bodies, properties such as stiffness are again defined in popups. Models of standard configurations can be stored as templates for further use, thus the generation of modified variants is easy and fast.

5.2 Simulation

Once the model and the boundary conditions (engine RPM, etc) are defined the simulation can be executed. For complex models and long simulation runs (several engine cycles) this can be a fairly time-consuming process. Simulation jobs running for over 10 hours are not uncommon. The resulting files can be as large as 1 GB.

5.3 Evaluation of Results

When the simulation has finished the user can launch the visualization tool Impress and load the results. The Impress application shown in Figure 10 has a tree view of objects on the left, can have any number of independent 3D viewing windows plus the standard menu and icon bars.

5.3.1 Managing Rigid Body Systems in Impress

Groups of bodies, e.g bodies that belong to one chain are created automatically. These groups are referred to as *systems* and they are displayed in the tree. The user can show or hide the components of the systems shown in Figure 3 as well as customize their colors and sizes. It is possible to hide or drag groups that are temporarily out of interest in order to reduce occlusion. Dragged objects can be returned to their original position by a single click.

The view can be panned, rotated and zoomed as desired. The model can be animated using VCR-like controls. The user can perform all tasks during animation, too. They can change the view-

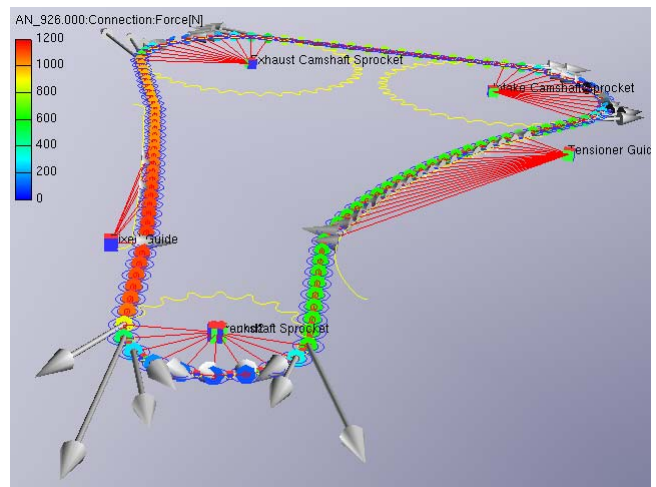


Figure 11: Forces between chain links (colored disks) and contact forces between chain links and sprockets (arrows) This figure also demonstrates the capability of creating several visualization objects simultaneously.

point, adjust properties of objects and create new visualization objects.

5.3.2 Visualizing Attributes

In order to view attributes of bodies or connections in a system the users selects the system and clicks the icons "Rigid body results" or "Connection results", respectively. A *visualization object* consisting of a group of glyphs referring to the bodies is created. A dialog pops up where the user can select the attribute and glyph type shown as well as customize glyph parameters. Any number of these visualization objects can be created for each system, and they can be hidden or dragged just like the systems themselves.

The engineers typically start exploration by examining if the simulation was correctly set up. They run the animation looking for obvious signs of incorrect initial conditions. Mismatching chain and sprocket contours, sprockets defined at the wrongs position or in the wrong orientation are very easy to spot. With toothed belt drives, loose tensioners may allow the belt to skip one tooth of the pulley, which is also very noticeable in the animation. These errors are very hard to discover without interactive visualization.

Then they proceed by examining forces along the chain drive, looking for areas of extremely high forces. These areas are quickly found by creating colored disks and running the animation. In Figure 11 the span of the chain on the left entering the sprocket is easily identified as being under heavy tension. Engineers are interested in the contact position and contact force of the chain links and the sprockets. This information is valuable in order to understand which areas will be subjected to extreme wear. In Figure 11 the location and direction of these forces is immediately seen which was not possible at all with the diagrams used before.

The vibrational motion of chain links in long spans can also be of interest to the engineer. This can be visualized by showing the translational and angular velocities of chain links as seen in Figure 12. In this case showing only the normal component of the velocity is highly useful.

Rotational acceleration and torque are very well visualized using the spirals introduced in Section 4.5. Figure 13 shows a close-up of rotational acceleration of chain links. It is clearly seen in the image that chain links undergo heavy acceleration as they hit the yellow

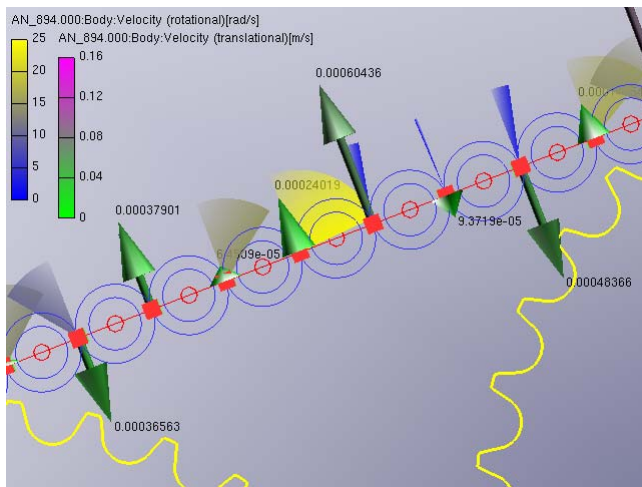


Figure 12: Rotational velocity of chain links visualized using the sector glyph. Annotated arrows show the normal component of the translational velocity. Vibrational behavior is clearly seen.

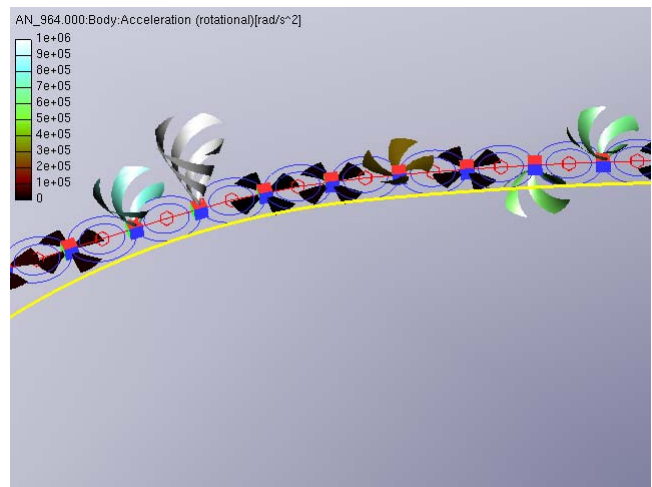


Figure 13: Rotational acceleration depicted by spiral glyphs. Opposing directions of rotation are distinguished by opposite twist directions and different orientation of the cone, too.

tensioner guide. This can be an indication to the engineer to change the profile of the tensioner to allow smoother contact. Naturally, this can reduce noise levels and the extend the chain's life span.

We must mention that not all types of color scales used are perceptually uniform [Levkowitz 1996]. The one seen in Figure 11 for instance has a large section of green colors which are hard to distinguish. Actually, this is not a disadvantage because users are generally more interested in the extremely small or large magnitudes.

We must not forget that interactive 3D visualization cannot entirely replace the traditional 2D diagrams. However, they can co-exist as means of partly different evaluation tasks. Interactive 3D visualization helps in exploration, locating areas and attributes of interest, whereas engineers will always refer to diagrams or actual numbers for more accurate information. Body names can be displayed optionally to assist looking up the corresponding diagrams.

All settings are saved in a project file to allow the user to continue exactly where they left off. There is a movie director module similar to the track view found in 3D Studio Max [3ds n. d.] to facilitate creation of AVI or MPEG movies for presentations. The user can define events that will be executed at given frames. Events include show/hide objects, zoom in/out, rotate view, etc. An event can be assigned to a range of frames. This enables smooth zooms and rotations, for example.

6 Evaluation

For many years experienced engineers have been using the 2D diagrams quite effectively. However, they still face difficulties understanding position and orientation of bodies as well as directions in 3D space. It is especially difficult to judge and compare relative positions and distances. Characteristics of periodic behavior such as frequency of vibration are also hard to perceive without animation. The visualization system we have described remedies these shortcomings.

6.1 User Feedback

Users have stressed the following advantages to their previous workflow:

- Contours that are in contact and actual positions of contact points are clearly identified. This is especially important if the model is somehow incorrect, for example the contour of a sprocket is not continuous. Discovering a very loose toothed belt that skips the teeth of a pulley as seen in Figure 14 is also made very easy. Errors in modelling and initial conditions became a lot easier to detect. Finding these types of problems used to be a slow process because the only indication had been irrational simulation results.
- Directions of forces are made clear. This is important when the engineer expects a force to act in one direction, but simulation proves that it acts in some other direction. In fact showing the direction and magnitude of vector attributes at the same time is something they could not do before.
- Motion of tensioners can be seen clearly. This has also been very difficult to understand by studying diagrams.
- Animation shows all chain links at a given time step creating an overall impression of how the chain moves. The graphs are created per chain link and the overall motion is not seen in them.
- It is easier to spot periodic behavior at a given point in space.
- Distribution of forces between chain links is seen. Areas of extreme tension can be found very quickly.

Less experienced engineers and professionals working in neighboring fields (manufacturing, namely) can also profit a lot from the more accessible presentation of the simulation results. Furthermore, advantages of 3D visualization for the marketing department are obvious. Convincing movies for presentations can be generated with little effort.

It is clear that interactive 3D visualization enhanced the existing application significantly. All user groups ranging from inexperienced, young engineers through experienced professionals to marketing department benefit from our solution.

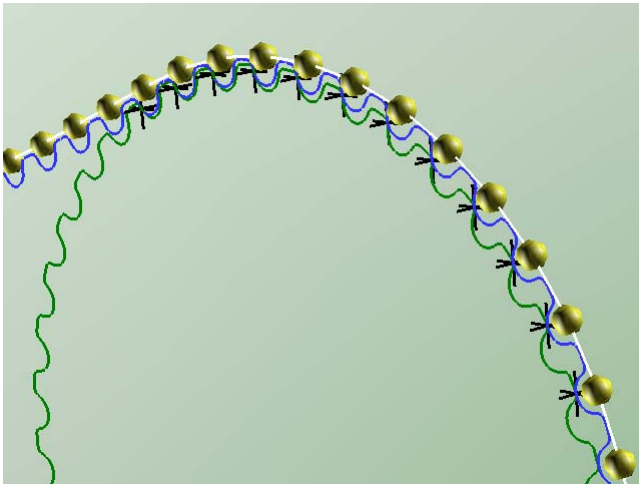


Figure 14: A toothed belt skipping over the teeth of a sprocket due to a loose tensioner. Contact points are depicted by black crosses. This phenomenon is very difficult to spot without 3D visualization.

6.2 Performance

Our implementation of rigid body visualization integrated into Impress runs on Windows 2000, Linux and various Unix systems. Naturally, performance depends heavily on the capabilities of the graphics hardware. Our tests were performed on a 1 GHz Pentium III with HP Visualize *fx* graphics accelerator and running Red Hat Linux 7.2. Rendering and navigation – implemented in a separate thread – runs at over 40 frames per second for typical scenarios. Animation of the chain model consisting of 134 chain links shown in Figure 11 updates at around 15 frames per second. Response to user interaction is generally immediate; creating new visualization objects requires about a second, though.

7 Conclusion and Future Work

Up to now little effort has been invested into visualization of rigid body dynamics in the automotive industry. Engineers were using 2D diagrams to evaluate simulation results. We have proven that interactive 3D visualization improves exploration and analysis significantly. The animated 3D view of the chain drive makes it easier to discover phenomena that were obscured before. Perception of position and direction has been enhanced remarkably. Understanding correlations of various attributes is also easier. These are valuable and welcome achievements even for experienced engineers. Our solution can be useful in training novice engineers and communicating simulation results to professionals not working directly with simulation. Finally, the capability of generating movies showing actual motion and attributes is an important feature when creating presentation.

Future work can extend in multiple directions. Users have already asked for the capability of positioning glyphs at given points in space. However, the simulator computes attributes that are valid at the actual position of the chain link they belong to. Therefore the value these glyphs visualize should be interpolated from the attributes of the chain links in the vicinity of the glyph's location.

There is also interest in integrating the visualization module in Tycon itself to facilitate instant model verification in 3D.

Aesthetic value can be enhanced by attaching surfaces to the bodies that resemble the actual object. This is not very straightforward though, because in Tycon no such model of the bodies exists.

Currently we visualize raw simulation results only. Visualizing derived attributes and states such as vibration would probably open new possibilities in the application.

Finally, we are also planning to introduce similar glyph-based visualization for flexible body simulation.

Acknowledgements

We would like to thank AVL List GmbH (www.avl.com) for their support and help. Parts of this work were carried out in the scope of applied and basic research at the VRVis (www.vrvis.at) which is funded by an Austrian governmental research program called Kplus. We also thank Robert S. Laramée of VRVis and Wolfgang Hellinger, Mark A. Mitterdorfer, Martin Sopouch and Christian Vock of AVL for their valuable contributions and feedback. All simulation data sets displayed in this paper appear courtesy of AVL.

References

- 3D Studio Max, <http://www.discreet.com>.
- AVL List GmbH, <http://www.avl.com>.
- BARAFF, D. 1989. Analytical Methods For Dynamic Simulation Of Non-penetrating Rigid Bodies. *Computer Graphics* 23, 3, 223–232.
- DE LEEUW, W., AND VAN WIJK, J. 1993. A Probe For Local Flow Field Visualization. In *Proceedings Visualization '93*, IEEE Computer Society Press, Los Alamitos, CA, G. Nielson and R. Bergeron, Eds., 39–45.
- HOFFMAN, D., AND DOWLING, D. 1999. Modeling Fully Coupled Rigid Engine Dynamics And Vibrations. In *SAE Noise & Vibrations Conference & Exposition*.
- LEVKOWITZ, H. 1996. Perceptual Steps Along Color Scales. *International Journal of Imaging Systems and Technology* 7, 97–101.
- MIRTICH, B., AND CANNY, J. F. 1995. Impulse-based Simulation Of Rigid Bodies. In *Symposium on Interactive 3D Graphics*, 181–188, 217.
- MIRTICH, B., AND CANNY, J. F. 1996. Hybrid Simulation: Combining Constraints And Impulses. In *Proceedings of First Workshop on Simulation and Interaction in Virtual Environments*.
- NIEMANN, G., AND WINTER, H. 1986. *Maschinenelemente*. Springer-Verlag.
- PARK, J., AND FUSSELL, D. S. 1997. Forward Dynamics Based Realistic Animation Of Rigid Bodies. *Computers and Graphics* 21, 4 (–), 483–496.
- POST, F., VAN WALSUM, T., POST, F., AND SILVER, D. 1995. Iconic Techniques For Feature Visualization. In *Proceedings of the 6th IEEE Visualization Conference*, IEEE Computer Society Press, 288–295.
- SAUER, J., AND SCHÖMER, E. 1998. A Constraint-based Approach To Rigid Body Dynamics For Virtual Reality Applications. In *Proceedings of the ACM symposium on Virtual reality software and technology 1998*, ACM Press, 153–162.
- TUFTE, E. R. 1986. *The Visual Display Of Quantitative Information*. Graphics Press.
- VAN WALSUM, T., POST, F., SILVER, D., AND POST, F. 1996. Feature Extraction And Iconic Visualization. *IEEE Transactions on Visualization and Computer Graphics* 2(2) (June), 111–119.