Virtual Prototyping Examples for Automotive Industries

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Abstract

The vision of virtual prototyping is to use virtual reality techniques for design evaluations and presentations based on a digital model instead of physical prototypes. In the automotive industries, CAD and CAE systems are widely used. This provides a good basis for virtual prototyping. This vision is therefore extremely interesting for automotive industries. Many companies have started to evaluate existing tools and technologies, and think about, or begin to develop virtual prototyping systems for their own needs. In this paper, we present some examples from our recent projects with automotive campanies. Based on these examples, we discuss problems, solutions and future directions of R&D to achieve the vision of virtual prototyping.

Keywords: virtual prototyping, virtual reality, functional simulation, interactive visualization, interaction techniques, object behaviors

1 Introduction

In the product development process, prototyping is an essential step. Prototypes represent important features of a product, which are to be investigated, evaluated, and improved. They are used to prove design alternatives, to do engineering analysis, manufacturing planning, support managment decisions, and often just to show a product to the customers.

Making physical prototypes is very time consuming and expensive. To shorten the product development time, design evaluations have to be done faster, the results must be directly incorporated into the design process. As CAD and CAE system are widely used in the automotive design, a lot of product data are digitally available. This provides a good basis for design evaluations, manufacturing planning and product presentation electronically.

In the industrial praxis, a lot of design evaluations are already done electronically using simulation systems. But physical prototypes are still used in the most cases. The benefits of physical prototypes rise from their spatial presence. Especially for conceptual design and product presentation, one can touch it, take them into the hand, and manipulate it to see if it works properly. Therefore, electronic prototyping asks for better man-machine interfaces. Virtual reality is the enabling technology providing realistic presentation and intuitive, direct manipulation of digital models.

In the beginning of this decade, virtual reality was regarded to be more a toy than a tool. The use of new, but today well known virtual reality peripherals, the head mounted displays and gloves, in the entertainment business has established this image. Press article and TV contributions reported on virtual worlds as computer generated alternatives to the real world. This created overall fascination about the new possibilities with virtual reality technology and supported science fiction impressions more than providing information. The social impacts of virtual environments were discussed and criticized very intensively even before first results were available from scientific-technical research and development work. But in the last few years, the development in the scientific world has made great success. Tools and systems are realized with which the technical, practical use of virtual reality technology has been demonstrated for different application domains. First examples were walk-through presentations for architectural design, interior design and urban planning. Recently, also automotive and aeronautic industries began to investigate this technology.

IGD started its VR research and development in 1993 with the VR Demonstration Centre initiative [10, 11] of the Fraunhofer Gesellschaft in Germany, one of the biggest research organizations carrying out applied research with industry. Since that, we performed a lot of VR research and developed our proprietary tools and the VirtualDesign system [1]. At the same time, the idea and concept of virtual prototyping was developed [3, 4], and several projects has been carried out together with industrial partners. The basic idea is to integrate CAD/CAE and VR techniques, and to assign the virtual objects with functionalities of the designed product, which implies the development of integrated simulation and visualization modules.

Following, we present our approach and experience of doing virtual prototyping with examples from our recent projects with automotive companies.

2 The sample projects

The descriptions of techniques, problems and solutions in this paper are based mainly on three projects we carried out, and are doing with automotive companies. All implementation was done using IGD's proprietary VR software "VirtualDesign II"[1] and corresponding tools.

In this section, we describe briefly the objectives of these projects.

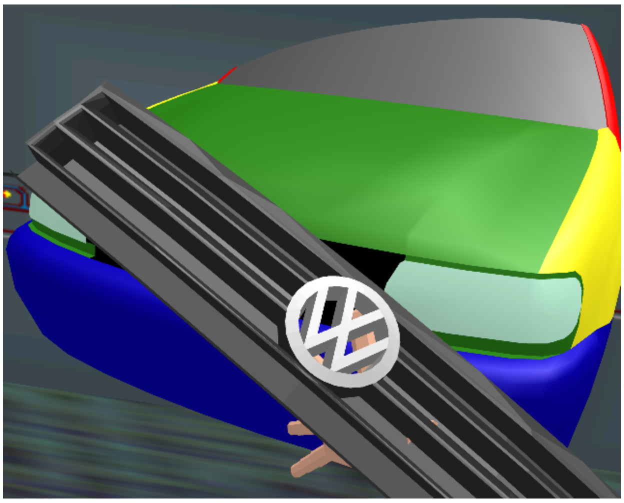

Figure 1: An assembly scene from the VW project. Data courtesy of Volkswagen AG.

2.1 The Volkswagen Project

In 1994, Volkswagen started to investigate the possibilities of VR in vehicle development and in the planning of manufacturing processes. Background reason is the very expensive process of developing a new car and the long time it takes to develop (four to five years elapse time between the initial design stage and actual series productions). During this time several steps are taken simultaneously. Machine tools are manufactured while the vehicle itself is still undergoing constructional development and tests.

Simultaneous Engineering Teams (SET) are set up to coordinate the various tasks involved. Particularly in the concept stages, it is difficult to identify inherent problems from the technical drawings. The teams have to try variant methods of assembly, analyzing separate functions and steps in the production process. Here, VR can help. Even at a very early stage, a virtual model can give the team a clear view of the present state of development, e.g., by presenting different ways of positioning and adjusting components in the engine compartment, and allowing simulation of alternative assembly procedures. Even the dismantling of a clutch unit could be simulated - which is important for the planning of subsequent maintenance.

The possibilities of VR technology range from support in factory planning, design and ergonomy to advertising. Soon, the customer in the dealer's showroom may be able to take a seat inside his virtual dream car, and select all the accessories and features he desires. VW's research division is collaborating with IGD since October 1994.

2.2 The BMW Virtual Seating-Buck

In 1995 IGD developed a "Virtual Seating-Buck" for BMW. This project focussed on the challenge of using VR to create a tighter integration between design and engineering analysis functions in the development process of automotive interiors (Figure 2).

It was necessary to address graphic display quality as well as functionality, and interaction techniques in order to provide the user with a convincing feeling of immersion into the virtual environment. To further increase this effect, a physical mock-up consisting of seat, steering wheel and foot pedals was built (Figure 3). Other hardware components included a tracking system, data glove and Fakespace's BOOM 3C.

One important aspect in order to intensify the user's feeling of immersion was the precise coupling between real objects and virtual objects. This was achieved by calibrating the virtual steering wheel with its physical counterpart (held by the user) and implementing a virtual feedback, such that the virtual steering wheel rotates simultaneously with the physical one. An accurate collision detection algorithm allowes us to realize this functionality without additional hardware, just using software to detect collision between hand and steering wheel and resolve the rotational constraints coupling the two.

Another point of interest was the embedding of CAE simulation results into the virtual environment demonstrated through flow visualization with interactive particle tracing of passenger compartment climatization simulation (Figure 14). Finally we addressed the use of VR for maintenance access verification and configuration studies (Figure 13). Again, using real-time collision detection on a large scale, conditions such as system location, space allocation and stayout envelopes could be interactively evaluated taking the air condition/heating unit as an example.

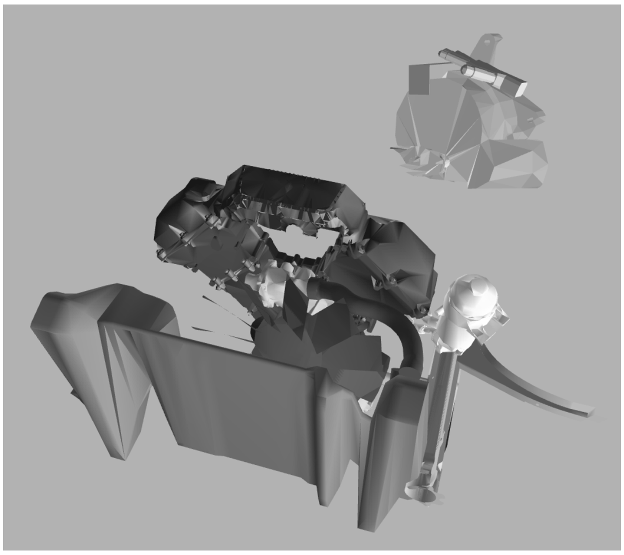

Figure 4: A scene from the AIT-demonstrator showing the selected engine part and a built-in simulation task. Data courtesy of AIT-consortium.

The system has been in prototypical use at BMW's R&D facility since November 1995 running on an SGI RE2 computer with two independent graphics subsystems. The results as well as user responses are promising.

2.3 The AIT-Demonstrator

To show the future vision of Digital-Mock-Up, and on behalf of the AIT-consortium [1], IGD has implemented a demonstrator and presented it at the AIT event in Darmstadt on 21. and 22. June 1995.

The goal of the demonstrator is not to show state-of-the-art of virtual reality, but to give an impression of how virtual reality can be applied

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[1] AIT — Advanced Information Technology in Design and Manufacturing (ESPRIT Project 7704). The project partners are: Aerospatiale, BMW, Saab, BMW, Rolls-Royce, Audi, Alenia, Dassault Aviation, Britisch Aerospace, Renault, Reydel, Mercedes-Benz, CASA, PSA, VW, Magneti Marelli, Fiat, Rover

Figure 2: The BMW Scenario. Data courtesy of BMW AG.

Figure 3: The physical equipment of the BMW virtual seating-buck.

to digital mock-up to support a rapid product development, especially discussions and decisions in the early design phase. Using the example of alternator exchange, the story illustrates the use of virtual reality techniques for the evaluation of design alternatives, for clash and clearance analysis, for assembly/disassembly simulations, and for the simulation of operation conditions.

In this demonstrator, nearly all important features of VR were demonstrated. Among these are: virtual menus, direct 3D manipulation, gestures, collision detection and response, kinematic constraints, deformation of flexible parts, visualization of technical data and simulation results.

For this demonstrator, BMW provided original CAD data of the 7 Series car body, the 8 cylinder engine compartment and technical information about the engine and alternators. TECOPLAN Informatics GmbH generated reduced polygonal data for the visualization. Vibration simulation data are provided by Mercedes-Benz AG, where TECOPLAN generated the geometry of the engine envelope. The DMU scenario and the corresponding requirements were defined by the AIT-Consortium to show the AIT-DMU approach.

These data were converted by IGD into the data format for VR, and prepared for the VR demonstrator. Furthermore, additional objects were modeled e.g. to build the virtual menus and displays.

The process of preparing data for virtual prototyping is described in the next section.

3 From CAD to VR

The first step needed before one can even think about doing virtual prototyping is the acquisition and preparation of the data.

3.1 Digital data and CAD data formats

Firstly, the data has to be available in a digital format. This may sound obvious, but there is no way to guarantee that all parts that are used e.g. in an engine come from the time of widespread CAD-systems. Even today a number of parts are in use that are older than 20 years, when nobody thought about using Computer Graphics for the design and manufacture planning of mechanical parts.

If the data is available, it has to be converted to a usable format. In the fast-paced computer world it is unlikely that all wanted parts have been modeled with the same CAD software, so that there has to be a common ground to build upon if the writing of a large number of native translators has to be prevented. In the automotive industry the problem is well known and there is an agreed upon and common format, which is VDAFS [5]. Nearly every CAD system used in the automotive industry has export facilities for this format. In a broader industrial spectrum the IGES format [18] takes this role as the lowest common denominator that is supported everywhere, which makes it an interesting target to support.

Of course, the vision of a more general, integrated product data model (STEP) [13] is very promising, and new developments in this direction (e.g. ProSTEP [17]) should be considered too.

3.2 Tessellation

One major problem for the transfer of CAD data into a VR system is the fact that the data is usually represented as free-form surfaces. This makes a lot of sense for the design and construction phase, but the real-time rendering of free-form surfaces is not yet supported by the available commercial hardware, even though interesting results have been achieved by university prototypes [16]. The commercial hardware is optimized for the fast rendering of flat polygons, especially for triangles. Thus the surfaces have to be tessellated.

Many CAD-systems have an integrated tessellation functionality for the output to e.g. stereolithography machinery or for finite element simulations, which are usually based on elements with planar boundaries. As this tessellation is not a trivial task, it might be worth the effort to use the built-in functionality and rather write an import for the tessellated format, which raises the issue of supporting multiple importers again. The optimal solution would be a CAD-system that supports a tessellated format that is usable by the VR system. The SGI OpenInventor format is starting to take this role. There are already systems that support a direct output to OpenInventor, and there is an increasing number of converters from other formats, e.g. IGES to OpenInventor. From the other end a large number of VR systems are starting to support OpenInventor import, because there is a nice reference implementation for an Inventor importer and in general Inventor offers easy access to the generated low-level primitives.

3.3 Complexity reduction

After these steps the model can be viewed in the VR system. In most cases it will not yet be usable. This is caused by the extreme size and complexity of tessellated CAD models. As a small example Figure 5 shows a wireframe picture of a tessellated engine. This engine is composed of 211 thousand polygons and is by no means very detailed. Even on the high-end hardware models of this size are hardly handable at all, not talking about VR applications, which demand at least 10 frames per second. Thus the complexity of the model has to be reduced.

This can be done at several points. Many tessellators offer a quality setting by adjusting error bounds while tessellating. These can be increased for the parts of the model that are not going to be in the focus of the task at hand. A problem with this approach appears at the edges of the surface patches. If a different error bound has to be used for the patches that meet at a common edge cracks may appear. These cracks have to be filled by automatic or semi-automatic tools and may require manual corrections.

Another possibility is to work on the tessellated model by employing polygon reduction techniques. These techniques have been used especially in the context of 3D scanner data, but can also be used in the context of CAD data.

In general a context-based reduction is important. The available polygon budget has to be spent in the places that are important for the task one is aiming at. In this spirit the easiest and most effective reduction method is cutting away the parts that are not important. This can be done by defining a 3D volume in the virtual world. Obviously this method may reduce the completeness of the model, but the gains in terms of rendering speed are worth it.

Not only the number of polygons is important for the rendering speed, but also the way they are

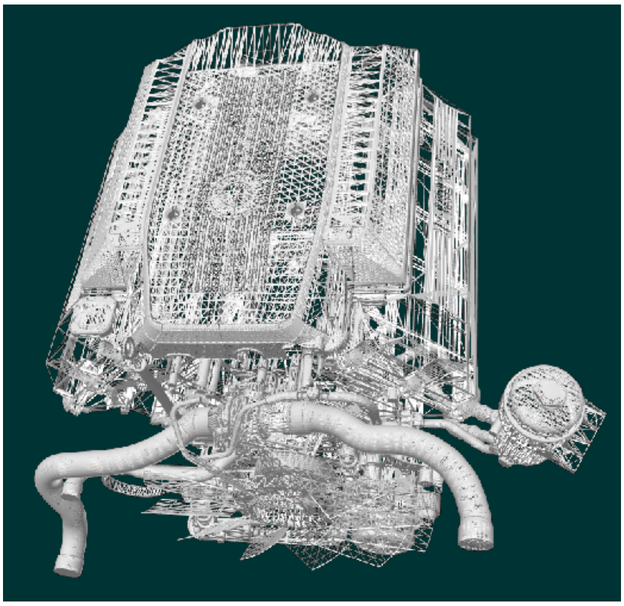

Figure 5: The CAD-geometry of an engine after tessellation. Data courtesy of AIT-consortium.

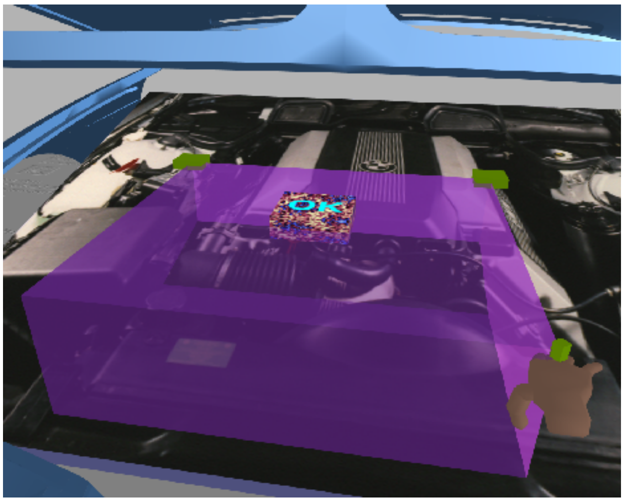

Figure 6: Selecting important parts using access-by-volume technique. The transparent box can be moved and scaled simply by grabbing one of its corner handles. Data courtesy of AIT-consortium.

presented to the rendering system. Many rendering systems feature specialized primitives for large models composed of triangles. Triangles that share a common edge can be joined together to form a triangular strip, reducing the amount of geometrical data nearly to a third and thus often increasing the rendering speed by a factor of 2 or more.

3.4 Optical, visual properties

When the model has been reduced to a usable complexity the next task is to add the visual information, which is usually not provided by the CAD system, to the model. This information consists of material properties like color and reflectivity, and the number and position of light sources to generate a convincingly realistic image of the data.

The result is something like Figure 4. In this picture the same engine scenario (see Figure 5) is shown, but the engine has been cut down and reduced to about 30,000 polygons. This scene can be rendered with more than 10 frames per second, which makes interactive and even immersive applications possible.

4 Functional Simulation and Visualization

An important aspect of Virtual Prototyping goes beyond the visual appearance. Virtual prototyping allows for a presentation of a product's design not only as a geometrical model but together with data which describe the object's functionality. With this capability virtual prototypes can be more useful in the product development process than physical prototypes. The latter group (still) suffers from the structural weakness of the materials used in most generative 'rapid prototyping' processes.

4.1 Object Functionalities

Three classes of product data are in focus for virtual prototyping beside geometry itself:

- Kinematics
- Structural mechanics
- Computational fluid dynamics (CFD)

While the mentioned product features are under investigation by engineers in the regular product development since long, it is not yet common to present them together with geometrical design studies. We see a great potential benefit in decision making when design alternatives of technical products are to be discussed between engineers, designers and managers. Virtual prototyping allows to investigate several product features with one single medium and in a manner suitable for non-technicians, too. Kinematics analysis of rigid body assemblies are practical in real-time with todays computers, and can be realized as built-in functionalities of a VP system (see Section 5.2). However, computational structural analysis and computational fluid dynamics are extremely computing intensive and their application requires expert knowledge, so that real-time simulation of real-world products during design discussions will still be 'science fiction' for a long time. The practical approach is immersive visualization of CAE data.

4.2 Strategies of Immersive Data Visualization

From a software engineering point of view, we identify five different strategies to realize the immersive (i.e. VR-) presentation of product simulation data [12]:

I. Extending an existing, advanced scientific visualization (SciVis) system with additional VR capabilities;

II. Extending an existing, advanced VR system with additional scientific visualization capabilities.

III. Creating a new system with some VR and some SciVis capabilities.

IV. Using an existing VR System to investigate (visualization) objects pre-computed by an existing SciVis System.

V. Integrating an existing VR System and a SciVis System with process communication via UNIX sockets or shared memory.

Strategy I has two major drawbacks: First, the 2D-point-and-click user interfaces of conventional SciVis Systems are not feasible for a VR presentation. Furthermore, the visualization algorithms of existing SciVis Systems are generally not tailored to produce the visualization objects at a frame rate suitable for immersive investigation. Strategy II requires the re-implementation of visualization algorithms. However, experience shows that the need for a high frame rate requires special data structures as well as special visualization algorithms, anyhow. Writing a new system from scratch (strategy III) requires huge man-power or will lead to an inflexible system for a special application. While strategy IV is simple but non-interactive, alternative V seems to be promising because nothing has to be re-implemented. But again, practice shows here that communication via sockets is neither secure nor deterministically regarding the response times. Also, we face again the fact that visualization algorithms of existing SciVis systems are usually not fast enough for VR requirements — at least not with huge data sets.

It is sad but it is true - user interaction is the main problem in immersive data visualization, regardless of which of the above mentioned strategies is applied. As long as speech input is not realized sufficiently, the interaction for configuration and control of visualization algorithms will be a big problem.

In the last years we have investigated strategies I, II, IV and V and found number two to be the most practical alternative. The next section describes two recent CFD-applications of immersive data visualization that where realized by adding a SciVis module to our VR system 'VirtualDesign II'.

4.3 Immersive Investigation of CFD Data

We have developed a flow-visualization module for our VR system 'VirtualDesign II' in order to integrate product simulation data with geometrical design studies. While we demonstrated the interactive analysis of the flow around a Volkswagen Polo at the Hannover Messe '95, we realized the immersive investigation of the Volkswagen TDI (Turbo Direct Injection) Diesel engine for the IAA '95 in Frankfurt.

Most impressive in flow visualization is the interactive particle tracing in the velocity field. Unfortunately, most flow simulations are carried out on unstructured Finite Element grids. Visualization algorithms for such grids require much more computational effort than those for regular or curvilinear computational grids [9]. Our investigations have shown that real-time particle tracing at VR-frame rates is only feasible on regular grids or (in the computational space of) curvilinear grids if hundreds of particles are to be advected simultaneously. Therefore, we re-sample unstructured CFD grids to a regular grid of adjustable spatial extension and density - being aware of the fact that we trade visualization speed against accuracy.

Our particle tracing module allows the release of particles at sources which are either coupled to the user's hand(-echo) or which can be positioned freely in the 3D scene by the user. The later alternative allows to position a fixed particle source and walk around in the scene in order to watch the advected particles from different points of view. The particles, which are rendered usually as flat squares, may be rotated by the rotational component of the velocity field (rot v) and/or may be connected to form streaklines. For transient flow data we provide streamribbons as an alternative visualization technique. Furthermore, particles or ribbons can be colourcoded according to the local speed or according to any other scalar data of the simulation results (Figure 7).

Other SciVis techniques that fit also well into the concept of immersive and intuitive exploration of virtual prototypes are those techniques that require spatial interaction by the user. Beside particle tracing, this is slicing and point probing [20]. We plan to integrate these techniques in a future version of our SciVis module. Another visualization technique which is of great use for structural analysis as well as for CFD data — and which is already available in the VR system — is object deformation. Imagine a crash simulation of a whole car that can be inspected interactively with a free navigation of the user in space and in time. In the application of the visualization of the TDI engine (see Figure 8) we animate the piston as well as the valves during the flow visualization. The diesel particles whose movements and momentary masses were pre-computed in a Lagrangian form by the CFD program are animated, too. Isosurfaces of the temperature serve as an indicator of the momentary location of the flames when the air/diesel mixture is burning.

5 Interaction with a Virtual Prototype

As already mentioned, interaction with the virtual prototype is a very important, but also difficult task. In this section, we describe some basic VR techniques and show our approach used in the sample scenarios.

5.1 Basic Input Techniques

In order to accomplish the interaction tasks, it is highly desirable to develop interaction techniques which are as intuitive as possible. Conventional interaction devices (keyboard, mouse, tablet, etc.) are not fit for natural interaction with most VR applications. One of the more intuitive ways is the "virtual trackball" or the "rolling trackball", which both utilize the mouse [15, p. 51 ff].

The shortcoming of all of the above mentioned devices is their low input dimension (at most 2). However, new devices like SpaceMouse, DataGlove, tracking systems, Boom, Cricket, etc., provide 6 and more dimensions. These allow highly efficient, natural interaction techniques. One of them is **gesture recognition.**

Usually, static gestures like "fist", "hitch-hike" are used for triggering actions. Gestures can be expanded by taking also the orientation of the glove's tracker into account (for example, to make simulation time go faster or slower). Gestures plus orientation is what we call *postures.* There is also research going on to recognize *dynamic gestures* which consist of a continuous sequence of static postures.

Gestures are very well suited to trigger simple actions, like program exit, display of a menu, or one of the following **navigation** actions.

Navigation comprises all forms of controlling the viewpoint in a virtual environment, or steering of a real exploration device (e.g., the repair

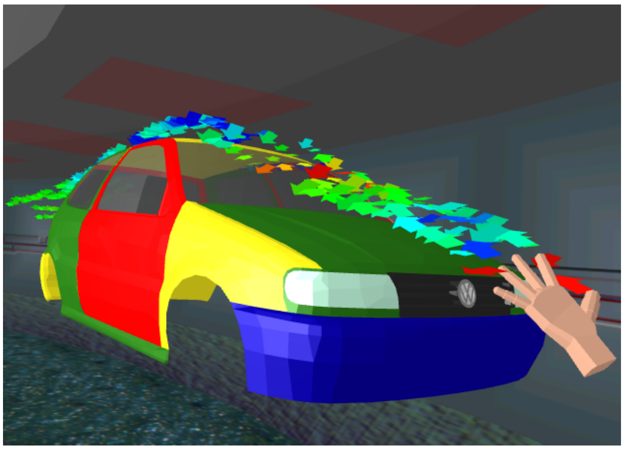

Figure 7: Immersive CFD investigation: Particles, colourcoded according to local pressure, indicate the flow around a Polo car. Data courtesy of Volkswagen AG.

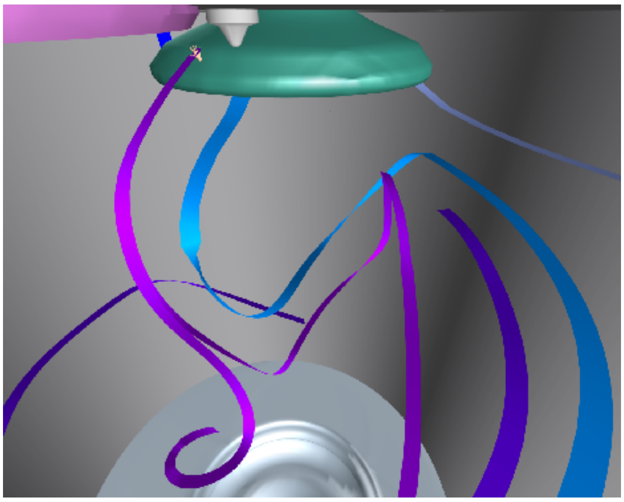

Figure 8: VR investigation of a diesel cylinder. Top: Valves and diesel nozzle. Bottom: Piston. Streamribbons of the velocity field emerge moving and stationary sources. Data courtesy of Volkswagen AG.

robot or the microscope needle). Most techniques can be derived from a single model, which assumes the virtual camera mounted on a virtual cart, also sometimes referred to as *flying carpet* (see also [22, 19, 7, 6]).

- In *point-and-fly* the user moves the cart by pointing in the desired direction with their navigation device (e.g., glove or cricket) and making a certain gesture or pressing a certain button. The speed of the motion can be controlled by the user the flexion value or the pressure on the button.
- *eyeball-in-hand*: this paradigm is accomplished by connecting the viewpoint and the viewing direction directly to a tracking system (e.g., an electro-magnetic sensor or a Boom). This technique is most appropriate for close examination of single objects from different viewpoints, e.g., interior design (see Fig. 9).
- *scene-in-hand*: this is the dual technique to eyeball-in-hand. The viewpoint is modified by the inverse transformations as with the eyeball-in-hand technique.

3D menus are a straight-forward extension of the well-known 2D menus to suit the full 3D approach of VR applications (see [14]). Usually their appearance is triggered by a gesture or a button. Several possibilities have been tested for the selection of menu items: shooting a ray through the index finger, shooting a ray from the eye through the index finger, or actually hitting the 3D button with the finger.

5.2 Object Behaviors

As mentioned in section 4, an important goal of virtual prototyping is to investigate functionalities of a designed product. Some of them can be simulated in real-time, so that an investigation in the form of "plug and play" can be done in the virtual world.

One example is kinematics simulation. Figure 10 shows a crank shaft, whose motion is simulated with a built-in kinematics module. Using

Figure 9: In interior design, for example, the eyeball-in-hand navigation technique is used, since the user holds, say, a Boom in his hands. Data courtesy of BMW AG.

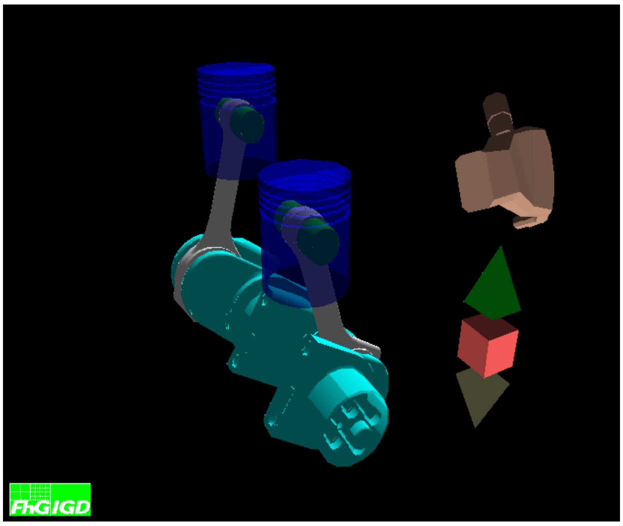

Figure 10: A rotating crank shaft. This simulation was shown as part of a VW scenario presented on the Hannover Messe '95

virtual buttons, it's velocity can be changed continuously.

Another example is simulation of flexible parts. Using such built-in simulations, modeling/deforming of objects can be done simply by pressing or dragging at the surface of an object (Figure 11). The user can manipulate any facet, i.e., vertex, edge, or polygon.

In order to achieve a realistic behavior, the manipulation should affect also the neighborhood[2]. This influence might be determined by predefined weighting functions, or it might be based on the preservation of physical properties (e.g., volume, or surface), or on other constraints.

Other representations like B-Spline surfaces, NURBS, or even CSG might be useful, or even necessary.

Of course, more complex and very accurate object behavior requires great computational resources both in terms of CPU power and in terms of clever algorithms.

But even using relatively simple, not necessaryly accurate, physical constraints, the manipulation of objects can be done in a more intuitive manner.

5.3 Intuitive Manipulations

An every-day task is the displacement of objects. As in the real world, the user should be able to do this by just pushing or pulling it with their hand, just like they would do it in reality (e.g. Figure 12).

Although it is highly desirable that objects behave naturally, we feel that the designer of a virtual environment has to decide on a case-by-case basis how close to reality certain interactions should be. For example, for many tasks, it is perfectly sufficient to let the user grab an object by just touching it while making a fist gesture (see Figure 4). However, for other scenarios, e.g. ergonomics analyses in engine maintainance, the grabbing should be modelled as close to reality as possible, otherwise no implications follow.

5.4 Collision Detection and Response

Another property of real objects is that they don't interpenetrate each other. *Collision detection* is

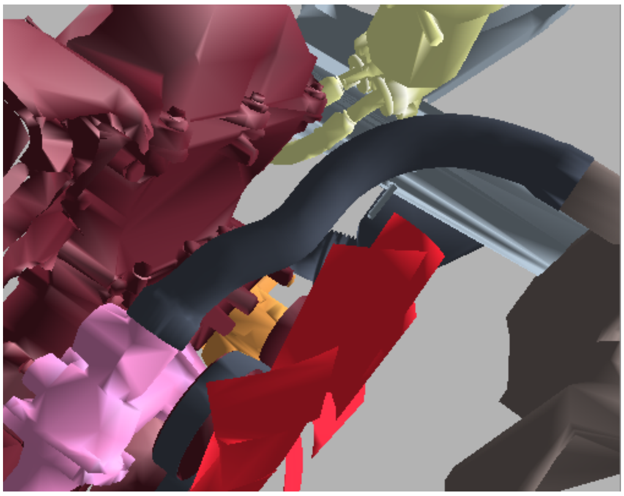

Figure 11: The cooling hose in the AIT scenario was modeled as flexible part. Pushing on it, one can get more space for assembling/disassembly the alternator. Data courtesy of AIT-consortium.

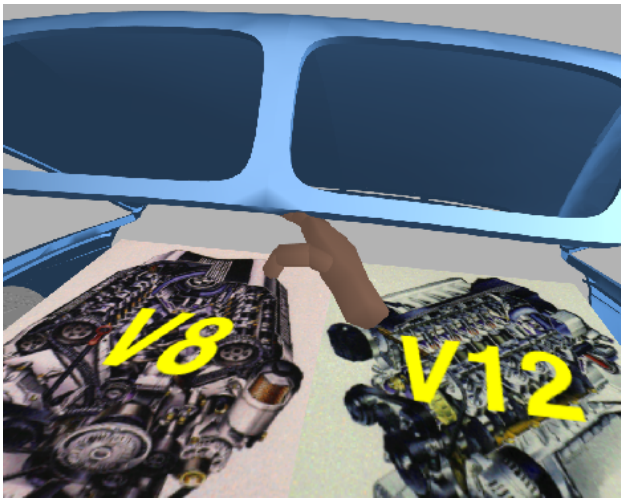

Figure 12: Lifting the hoode with kinematic constraints. Data courtesy of AIT-consortium.

very important for virtual worlds, too. However, *collision response* should not always resemble real-world behavior. For example, it might be very hard to place an object in a dense environment, when colliding objects keep sticking on each other (see [21]). Instead, a more suitable collision responses might be highlighting of colliding objects accompanied by some sound feedback (see Figure 13).

5.5 Interaction for visualization.

This is a pretty new field in the realm of virtual environments. By using 6D (or more) devices, new, and potentially much more efficient techniques for interaction with simulation results can be devised.

As mentioned above (Section 4), we have ported several visualization techniques for flow fields over to virtual environments. Common techniques are particle tracing, stream lines, and streak lines. For each of them, sources within the field have to be placed. With the aid of interaction techniques for virtual environments, it is very easy to place these: the user just grabs the object which represents the source and places it somewhere else in space. Or, even more efficient, the fingers of the virtual hand itself become sources (Figure 14).

6 Conclusions

A virtual prototyping environment bridges the gap between people with different technical backgrounds like designers, simulation engineers, managers, and customers. They can exchange their work results and ideas in a common, intuitive understandable form. They can easily make together experiments with the virtual objects, analyze the design and simulation results, and make modifications.

The results of our recent projects have shown, that there is a great potential of applying VR techniques, but at the same time, existing VR techniques have still many drawbacks. To achieve the vision of virtual prototyping, enormous efforts are still necessary both in the research community and in the industry. Only in such collaborations between research and application parties, the real problems can by identified and practical results can be achieved.

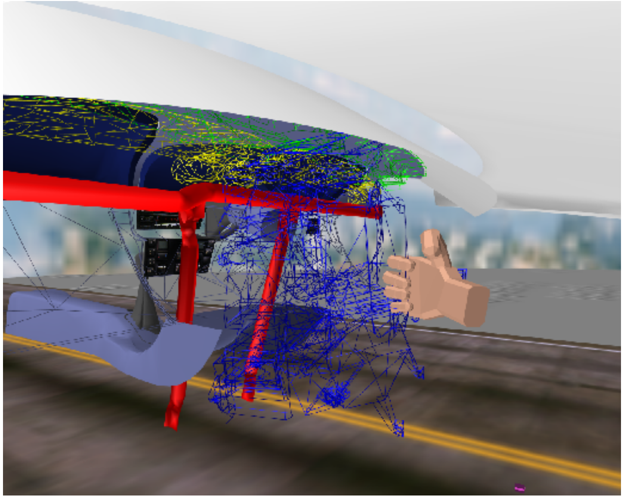

Figure 13: Collision response while moving an object must not interfere with smooth interaction. Here, collision response was chosen to be highlighting of colliding objects by wireframe and via sound feedback. Data courtesy of BMW AG.

Figure 14: The flow of air particles at the front window, with some fixed particle sources and the hand as a freely movable source. Data courtesy of BMW AG.

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Acknowledgement

We greatly thank the industrial partners i.e. Volkswagen AG, BMW AG, and the AIT consortium, who make our application-oriented R&D work possible.

Special thanks go to Mr. Th. Reuding (BMW), Mr. P. Zimmermann (VW) and Mr. P. Reindl (AIT/BMW) for their comments.

Also thanks to all colleagues and students, who contributed/supported the realization of the projects.