VIRTUAL INTEGRATED DESIGN AND CONSTRUCTION

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ABSTRACT: Recent surveys in the construction industry (e.g. Egan Report [1]) show that significant value improvement and cost reduction can be gained by substantially integrated solutions being applied by project teams as a mean of reengineering the project process. In particular, these surveys show that there are considerable benefits to be gained by integration of the "design" and "construction" processes.

After a brief presentation of potential applications of Virtual Reality (VR) in the construction industry, the paper will focus on the issue of "collaborative virtual prototyping". In particular, the research carried out in the frame of the CAVALCADE[1] project, funded under the European ESPRIT programme (HPCN[2] domain), will be presented. Special emphasis will be put on the concurrent engineering features of CAVALCADE allowing project teams, based in geographically distant locations, to collaboratively design, test and validate shared virtual prototypes.

As a conclusion, the objectives of new IST project (DIVERCITY[3] - Distributed Virtual Workspace for enhancing Communication within the Construction Industry) that will build, among others, on the results of CAVALCADE, will then be presented.

KEYWORDS: Virtual Reality, Virtual Environments, Collaborative Virtual Prototyping, 3D Real time Interaction, Construction.

1. INTRODUCTION

Compared to other industrial sectors, the construction industry faces several constraints:

- a high degree of complexity resulting from a high number of different, mostly small, companies working on one single project. These companies, usually geographically distant, are supposed to exchange an important amount of information during the construction processes. In reality, many processes are repeated due to the lack of communication, thus resulting in a waste of time and materials;

- high uncertainty caused by site conditions as well as modifications in the projects that can take place after the work has already started. This frequently leads to discontinuities between the design and the project execution;

- clients and indirect stakeholders (local authorities, residents, etc.) have, on the basis of 2D drawings, different and incomplete understandings of the planned construction. This

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[1] CAVALCADE (Collaborative Virtual Construction and Design) : Esprit project n°26 285. Started in January 1998 and was successfully closed in February 2000.

[2] High Performance Computing and Networking.

[3] IST project n°13365 . The start date of the project is March 2000.

frequently leads to client di-satisfication and problems discovered during post-occupancy evaluations.

Many of these constraints can be correctly dealt with by integrated solutions being applied to re-engineer the project process. In that respect, Virtual Prototyping tools can contribute in:

1. improving the co-ordination and communication between the different project partners and stakeholders around a visual, and thus intuitive, 3D representation of the planned construction ;

2. bridging the gap between design and engineering on one hand and construction on the other hand.

2. VIRTUAL REALITY IN THE CONSTRUCTION INDUSTRY

2.1. Some definitions

Numerous definitions have been given for Virtual Reality (or VR) and Virtual Environments (or VE). One of these definitions (by Sherman and Judkins – [2]) describes the characteristics of these technologies as the “five i’s”:

Intensive : the user concentrates on multiple and vital information.
Interactive: the user and the computer interact reciprocally by the mean of ad hoc devices.
Immersive: the user is deeply absorbed by what he sees.
Illustrative: the information presented to the user is concise, clear and descriptive.
Intuitive: the virtual information resembles to what the user is used to see in the real world.

Basically, this means that, compared to conventional computing, VR/VE applications present more intuitive and more inclusive user interfaces.

VR/VE systems can be roughly classified in two main categories (i) desktop systems and (ii) immersive systems.

- ***Desktop systems*** are based on conventional hardware where the user views and interacts with the computer through standard I/O devices (graphic screen, mouse, speakers, etc.). These systems can also be enhanced by the use of specific devices (stereoscopic glasses, spaceball, 3D mouse, etc.).

- ***Immersive systems*** are based on complex I/O devices (power gloves, position trackers, head-mounted devices, etc.). These devices are relatively expensive (even though their prices are decreasing) and require specific high-speed hardware making the cost of an immersive system considerably higher than a desktop system.

2.2. Potential applications of VR in the Construction industry

Even though VR/VE based tools can be useful in every stage of the construction process (in the design phase, construction phase, marketing phase, etc.), the “design phase” is probably where their impact is the most important. Indeed, decisions taken during the early design phase are of paramount importance due to their possibly dramatic effects on the planned project, timing and costs. Virtual prototyping allows:

1. to better capture the clients needs and therefore avoid client di-satisfaction and functional inefficiencies ;

2. to evaluate the design, very early in the process, in regards to different constraints (architectural, technical, financial, environmental, etc.) since virtual prototyping tools allow the design team to have a *quick and high quality feedback* on the project ;

3. to play *what-if* scenarios during the detailed design phase, in order to assess the proposed solutions from different technical points of view (structural, thermal, lighting, etc.).

2.3. Optimization algorithms.

Construction projects can very easily become complex. Therefore, performance optimization procedures are necessary to keep an acceptable frame rate during model inspection. Two optimization procedures are particularly efficient in the AEC sector: occlusion culling (when the walkthrough takes place in the first floor, there no point in loading the geometry of the other floors) and Level of Details (LOD): each of the building components (that can be very complex if represented with all their details) have several representations that will be displayed depending on the level of detail required based on the distant between the component and the point of view. Discrete LOD is a trivial application of this procedure where a predefined set of representations are associated to each component. Continuous LOD (detailed in §3.5) are a more complex and powerful application where different representations of each component are generated “on the fly” during the walkthrough.

These methods, combined with more generic optimization methods (such as back face culling and visibility culling) should allow complete scalability of the system independently of the complexity of the visualized project.

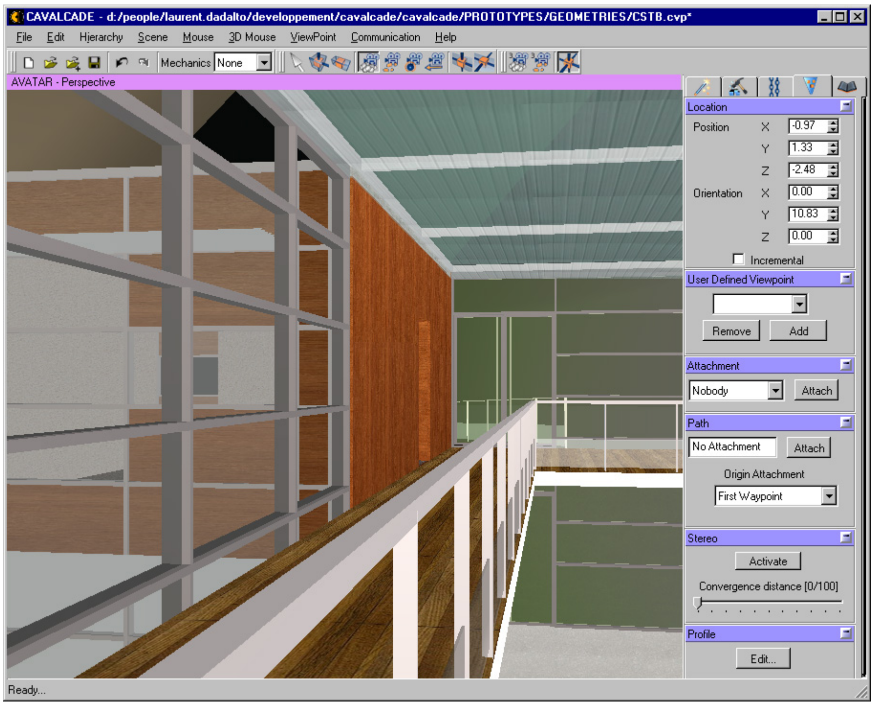
3. CAVALCADE: A COLLABORATIVE VIRTUAL PROTOTYPING TOOL

CAVALCADE’s goal was to develop a *Collaborative Virtual Prototyping* system. Using a distributed architecture, CAVALCADE system aims to support and enhance concurrent engineering practices therefore allowing teams based in different geographic locations to collaboratively design, test and validate shared virtual prototypes. Several industrial sectors were presented in the CAVALCADE consortium (construction industry, automotive industry, transport industry and aeronautical industry). These sectors shared a common vision: even though decisions taken during the design phase of engineering projects are often the most delicate ones, no adapted tools are available to support relevant inspection and evaluation of the design.

Physical mock-ups are routinely used for applications such as testing equipment integration, accessibility and space requirements in domains ranging from aerospace and automotive manufacturing to architecture. But these mock-ups are expensive to produce and do not allow complex inspection and evaluation.

The visual capabilities of present CAD tools are also much too limited to make interactive inspection and model manipulation possible. With such systems, it takes a fair amount of time and imagination to isolate design errors. Even more important, the lack of support for cooperative work makes information sharing among geographically remote people difficult.

Thus, large engineering projects have often been accompanied by the development of in-house virtual prototyping tools [3], showing the need for a general-purpose virtual prototyping solution that supports multi-site collaborations [4].



Mechanics: None

Position X: -0.97
Position Y: 1.33
Position Z: -2.48
Orientation X: 0.00
Orientation Y: 10.83
Orientation Z: 0.00
☐ Incremental

Attachment: Nobody

Path: No Attachment

Origin Attachment: First Waypoint

Convergence distance [0/100]

Figure 1: CAVALCADE interface

3.1. Methodologies and technologies

Natural interaction with digital mock-ups is very important, especially for testing purposes: by providing a virtual reality interface to the model, it is possible to give direct answers to important questions such as "can a short driver reach the controls on the dash ? Can an oil filter come straight out or does it have to be wiggled past some other components ?" [5].
In an attempt to overcome present CAD system interactivity and concurrent design limitations, large engineering projects have often been accompanied by the development of various kinds of specialised virtual prototyping tools. Examples include the ISS VR Demonstrator used by Rolls-Royce to make an assessment of how easy it would be to build an engine and maintain it [6] and Boeing's high-performance engineering visualisation system used during the design of the 777 [7]. Moreover, the French Space Agency (CNES) and CS-SI have jointly launched the PROVIS [8] research project in 1995 in order to develop software solutions for satellite designers to create, manipulate, and study their models using digital mock-ups. Meanwhile, CRS4 and CERN have jointly developed the i3d system for supporting the design of CERN's Large Hadron Collider [9]. These efforts show the interest of interactive virtual prototyping for early evaluation of design options.

The need for large-scale collaborative design tools has been recently recognised in the USA by the Defence Advanced Research Project Agency, which announced its support for the VELA project, the latter being a proof of concept for a globally distributed design of multimedia processor chips [10]. Recently, research and development efforts for building virtual prototyping systems have started independently from the need of a specific project. Ongoing research at the Fraunhofer Centre for Research in Computer Graphics is studying how to integrate existing tools to provide virtual prototyping capabilities to existing CAD systems [11]. Some recent CAD products add-ons such as Enovia from Dassault Systemes, EAI's eVis, PTC's dVise and EDS Unigraphics Modelling module follow the same direction, providing real-time visualisation capabilities for engineering designs.

Unfortunately, most of these solutions suffer from drawbacks concerning either 3D interaction or collaborative capabilities. The latter issue is for sure one of the less developed in the virtual prototyping software industry although most of the recent large projects have reached a world-wide dimension.

CAVALCADE aimed to overcome some of these limitations by providing a powerful and intuitive software solution for collaborative virtual prototyping that integrates recent advanced visualisation techniques in several technological areas including Distributed Virtual Reality (DVR), time-critical rendering techniques and 3D user interfaces.

3.2. CAVALCADE concepts and its software architecture

Within CAVALCADE, two main components were used in order to define a virtual environment: *entities* which encapsulate graphical objects and their behaviours; and *stimuli* which are the base of interaction and information exchange between entities. Both components are brought together in a *virtual universe* (Figure 2).

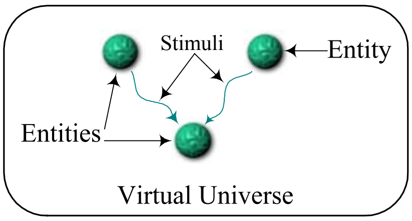


Figure 2: Virtual environment model

Moreover, in order to keep the model consistent, *avatar* entities have been introduced to act as interfaces between the virtual environment and users.

The purpose of this structure is to simplify the definition of distribution patterns. Autonomous entities lead to a perfect encapsulation of both the behaviour and the state of an entity, and therefore facilitate their distribution: such an entity can run its behaviour on any site communicating with other entities through well defined stimuli.

3.2.1. The communication model

The units of communication, *stimuli* (phenomena or events perceptible by an entity), are exchanged through media called *stimuli spaces*. The stimuli spaces have been introduced in order to permit communications and interactions between many entities simultaneously. Each stimuli space is in fact a projection of the environment along a specific type of stimulus (3D graphics' space, multimedia space...). An entity receives perceptible stimuli (3D objects, near sounds...) through *sensors* and acts on its environment through *effectors* (producing new stimuli) (Figure 3).

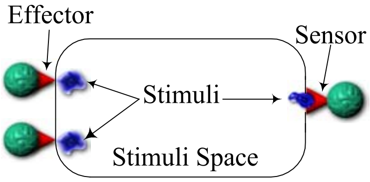


Figure 3: Communication model

3.2.2. Within an entity

We have introduced the entity paradigm in order to define in a generic way every kind of scene components. Entities can represent virtual objects, avatars or 3D tools.
An entity is defined by its *behaviour*, a set of *attributes*, a set of *sensors* and a set of *effectors*. Both sensors and effectors enable an entity to communicate with its surrounding environment while its attributes define its internal state. This model borrows a lot from behavioural simulation architectures [12] where very complex behaviours were successfully implemented (e.g. animal flocks, ant farms...). This is the reason why we chose such a model for the design of complex and dynamic virtual environments.

3.2.3. The software architecture

The CAVALCADE software architecture is made of a number of layered blocks. Each block being a piece of software which provides features to its upper blocks and uses the features provided by its lower blocks. The lower blocks are the network API (TCP/IP sockets in the current implementation) and the low level graphical API (currently OpenGL). Above these blocks are found general libraries like VERTIGO (a high level graphical toolkit based on the VRML97 standard) as well as other components developed within the CAVALCADE project: “VIPER” is a generic distributed platform, composed of a library and a set of servers which enables shared virtual environments to be built (cf. §3.4). “Now” is a set of C++ classes, designed to render large CAD databases under “time critical” conditions (cf. §3.5).
The top-most layer, “Behave” (cf. §3.3), provides the behavioural core of the application, using all other blocks in order to build a 3D, collaborative high performance tool for virtual prototyping.

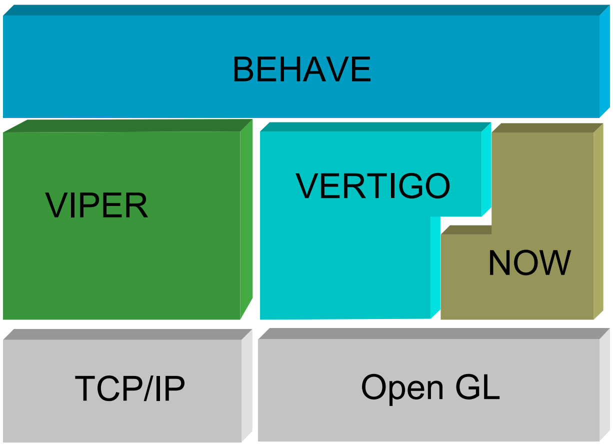


Figure 4 : The CAVALCADE architecture.

3.3. BEHAVE: CAVALCADE entities

This layer aims at providing the behavioural components which enable to create CAVALCADE entity behaviours, thus defining the final application. In its basic version, CALVALCADE is functionally defined by the following entities : the Builder, the GUI and several prototypes.

3.3.1. The Builder

The aim of this entity is to provide the user with high-level commands in order to build 3D prototypes. It manages the interaction process (multimodal dialogue) and the application’s specific functions (components assembly, documentation, etc.). In fact, it specifies the application’s functionality.

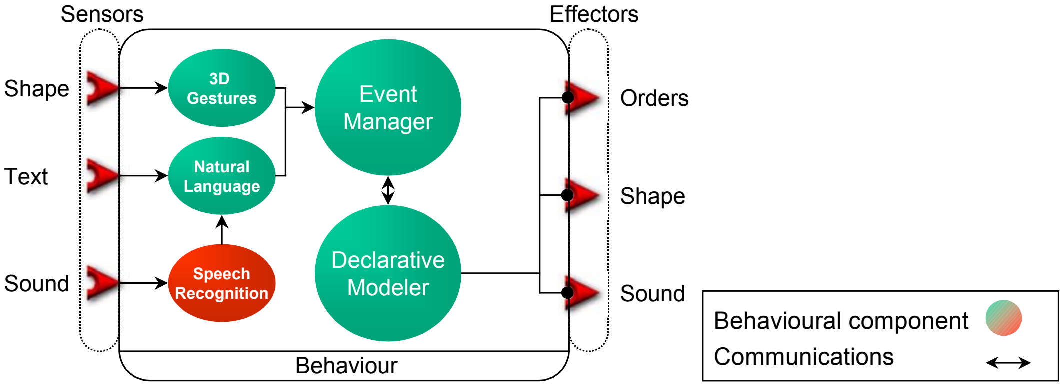


Figure 5: A simplified view of the Builder's behavioural components

3.3.2. The GUI

The Graphical User Interface is, in fact, a simple frame where other entities add or remove their own widgets. For instance, an entity adds its widgets by sending stimuli to the GUI. Thereafter, this entity will receive stimuli through a specific sensor, each time its widgets are activated.

Two kinds of objects are present in the GUI (Figure 6): the 2D and the 3D widgets. The 2D GUI is a set of menus, dialog areas and buttons which surround the 3D GUI. The latter is made of the rendering window and a set of 3D manipulators enabling to interact with prototypes.

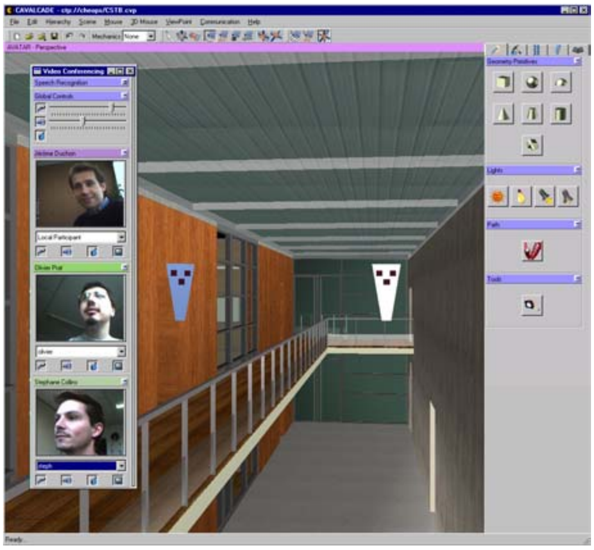


Figure 6: CAVALCADE GUI

3.3.3. The prototypes

The prototypes are also modelled according to the entity model. Thus, a 3D entity embed several behavioural components such as “Dynamics” to simulate forces and torque applied to the entity or “Documentation Access” to enable the user to browse associated online documentation browsing. The prototype stores all its documentation with an URL pointing toward a user-defined HTML page (Figure 7).

This page contains an HTML form which permits the edition of non 3D prototype properties and triggers access to external technical databases thanks to SQL request and ODBC[4] technology.

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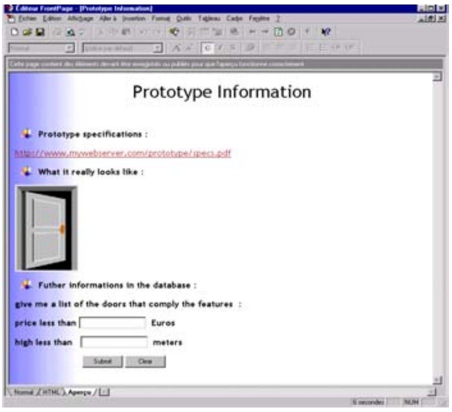
[4] Open DataBase Connectivity is a standard application program interface for accessing databases.



Prototype Information

Prototype specifications :

http://www.mywebserver.com/prototype/specs.pdf

What it really looks like :

Futher informations in the database :

give me a list of the doors that comply the features :

price less than Euros

high less than meters

Figure 7: Online documentation.

3.4. VIPER: Distributed Core

VIPER [13] is used within CAVALCADE to provide the necessary distributed architecture of such a collaborative application. It is a generic Distributed Virtual Reality system, like MASSIVE [14], DIVE [15] or VLNET [16], and has been created in order to support different types of applications.

3.4.1. Distributing entities

VIPER entities exist in two flavours: simple entities which are managed by the site where they have been created and duplicated entities which exist on a set of sites (usually all the sites which manage a given collaborative session). Duplicated entities may define duplicated attributes which are synchronised by VIPER on a set of sites (i.e. when such an attribute is modified on one site, all other sites copies of this attributes are updated).

3.4.2. Entity direct interactions

Direct interaction (i.e. when an entity manipulates other entities or sends them messages) in a distributed context implies that interacting entities may happen to reside on different sites. We have decided to model those interactions by exchanging *orders* (a subclass of stimuli) between entities within the framework of a specific distributed stimuli space. This space, called the *order space*, sends orders to interested entity sites using point to point communications through a server. The server permits the use of fewer connections between sites as in the case of a site to site direct connection but also permits the sending of orders to a set of sites (in order to manage duplicated entities). In the current implementation we use TCP[5] but we plan to use IP[6] multicasting for frequent and unimportant orders (e.g. position and orientation modification requests which are exchanged when an entity – for example the avatar – moves another one).

In order to send orders to the correct sites, the server translates the receiving entity ID to a site ID where the entity is stored. For duplicated entities, it sends the order to all sites in a given session (the session ID is also stored in orders). In the following figure, the server is hidden within the order space because its management is transparent to the programmer of the application. For example, there is absolutely no programming differences between the sending of an order to a local entity and the sending of the same order to a distant or duplicated one. The order space takes care of everything transparently.

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[5] Transmission Control Protocol is the reliable data transport protocol of TCP/IP (the Internet protocols Suite).

[6] Internet Protocol.

3.4.3. Transparent access to remote VRML files

The VRML space permits transparent download of VRML files from distant VRML servers (Figure 8).

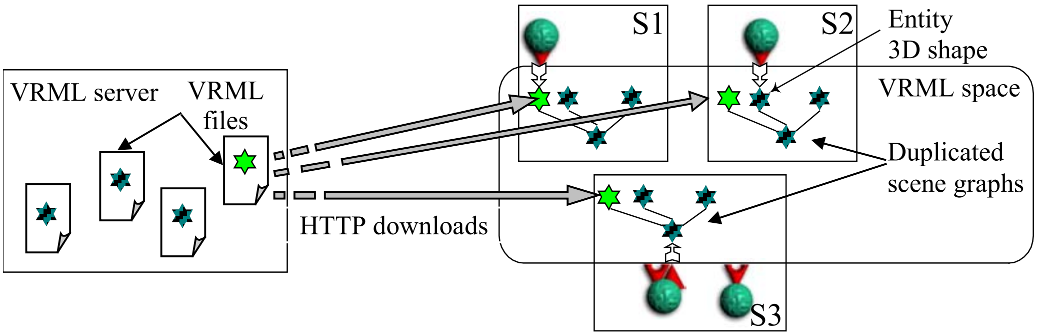

Figure 8: The VRML space and a VRML server

Those servers and the VIPER library use an HTTP-like protocol in order to permit the download of files as well as their upload when they need to be saved. Moreover, VIPER implements mechanisms enabling several users to work on the same VRML file (static and dynamic access rights).

It is important to note that all communications are hidden in the stimuli space and therefore an entity, as well as the programmer of the entity class, is not concerned with communication management details.

3.5. NOW: Optimising CAVALCADE for large CAD databases

The Now package is a set of C++ interfaces designed to render large CAD databases in "time critical" conditions. It provides automatic simplification algorithms for triangular meshes and level-of-detail management tools that are built on top of an efficient multiresolution structure [17].

3.5.1. Level of Details

Despite the continuous improvement in performance of CPUs and graphics' accelerators, scenes exceeding a million of polygons cannot be handled directly at interactive speeds even on high-end machines. The traditional approach is to pre-compute a small number of independent level-of-detail (LOD) representing each object composing the scene, and to choose at run-time the best one based on a cost/benefit analysis [18]. Even if LODs introduce a significant memory overhead, they are commonly used as they match easily with current "time critical" hardware and software architectures. Actually, as LODs are pre-computed, the polygons can be organised in the most efficient way (triangle strips, display list), exploiting raw graphics processing speed with retained-mode graphics. Moreover, LODs can be inserted directly into a scene graph architecture with minor changes in the rendering engine.

Therefore, the LOD approach is particularly adapted to a system like CAVALCADE, where the scene is modelled as a set of entities organised in a VRML scene graph.

3.5.2. Geometry simplification

Users of virtual prototyping systems do not want to deal with time critical issues when they conceive new prototypes. Therefore we have developed simplification algorithms to automatically create various representations of the CAVALCADE geometric entities.

As in [19], we implement mesh simplification schemes based on iterative vertex substitution in a generic framework of greedy algorithms for heuristic optimisation. The generic greedy algorithm is parameterised by a *binary oracle*, deciding which vertex substitutions are legal, and a *fairness predicate*, which assigns priorities to all vertex substitutions in the legal candidate sets. The algorithm proceeds in a series of greedy steps until the candidate set is empty. In each greedy step, the best vertex substitution is removed from the candidate set, the mesh is modified accordingly, and new substitutions are re-evaluated for the vertices affected by the mesh change. To speed-up these operations, the candidate set is implemented as a heap keyed on the priority, and references to the heap entries that have to be modified are associated to each of the active vertices. The *binary oracle* used to simplify CAVALCADE mesh selects vertex pairs that are in a predefined range. Our *fairness predicate* is assigning priorities using a linear function of volume variation, area variation, vertex pair distance and an additional penalty that avoids surface inversion. The mesh boundary preservation can also be controlled by adding a penalty to boundary vertices.

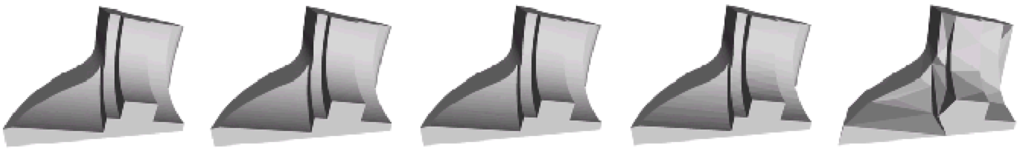

Figure 9: Fandisk model in various LOD (20%, 10%, 5%, 2%, 1%)

4. CONCLUSIONS

After years of being slow to change, the construction industry has finally started to be aware of the importance of Information Technologies, among which VR/VE applications, as a tool in construction process re-engineering. A recent survey conducted by ISI (Information Society Initiative) for the DTI (Department of Trade and Industry) in the UK yielded that Telecommunications and AEC are currently the two industrial sectors that show the most interest in VR/VE tools: 54% of the interviewed companies from the AEC sector (architects, construction companies, contractors, etc.) stated that they are interested in VR/VE based tools. This represents a very interesting potential market and shows that this market is now expecting input from technology. Technology providers should now take up the challenge in order to propose adapted tools that enable project team members to work collaboratively through one unique and coherent virtual representation of the planned construction.

The CAVALCADE system, described in this paper represents, a good basis for a generic collaborative design tool. Nevertheless, due to the composition of the Cavalcade consortium (where several industrial sectors were represented), this system still needs to be adapted to some specificities of the AEC sector.

The new IST project (DIVERCITY - Distributed Virtual Workspace for enhancing Communication within the Construction Industry) will build, among others, on the CAVALCADE system in order to propose a Distributed Virtual Workspace adapted to the AEC sector. In particular, the NOW library will be completed in order to support optimization of textured models resulting from lighting simulations (based on the Radiosity techniques) and the VERTIGO library will be used as the kernel of a Multi-Disciplinary Design tool (MDR) combining technical simulations (lighting, thermal and acoustic simulations), product modeling (based on an extension of IFCs) and fast rendering techniques (based on continuous LOD).

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