Real-time Immersive Visualization for Satellite Configuration and Version Comparison

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ABSTRACT

Spacecraft design and development is a complex task which requires a long lifecycle and many phases of iterative construction. Thus, there are usually many versions of configuration design evolving over time. A clear understanding and comparison of these different versions of spacecraft configurations can bring benefits to both stakeholders and domain experts of the project. However, usually the configuration and system data is stored in textual format in tables and in files which is not efficient to compare results by checking all the subsystem and parameters in different versions one by one. As an alternative, this paper gives a detailed insight how to compare versions by means of 3D visualization and Virtual Reality (VR) technologies. The basis of our approach is the Virtual Satellite (VirSat) which is the standard tool for concurrent engineering studies at the German Aerospace Center (DLR). The key performance indicators of an early space mission design are the mass, the power consumption, and the temperature. In order to highlight differences of these quantities and distribution of key performance indicators, the VirSat uses color coding for more intuitive understanding. To analyze the changes of geometry information, additional two visualization modes have been integrated for comparing and indicating the differences between versions. In the first mode, two versions of configurations are visually overlapped. The differences are indicated by special colors. In the second mode, different versions of the design yield a successive animation in order to follow the design evolution. Both modes require model transformation from VirSat's central system data model to visualization model which is used for appropriate visualization approaches. The paper gives a detailed architectural overview and discusses benefits and future opportunities.

INTRODUCTION

Nowadays, space system design and development is often conducted in special designed facilities such as the Concurrent Engineering Facility (CEF) at the German Aerospace Center (DLR) [1]. Domain experts, engineers, and customers work together and exchange ideas in an iterative way. The design parameters are collected and modified by means of software tailored for concurrent engineering studies [2]. The software helps experts to manage the configuration data, the exchange of interdisciplinary data, and data consistency. The Virtual Satellite (VirSat) is the standard tool for concurrent engineering studies at DLR [3, 4]. Following the Model-Based System Engineering (MBSE) paradigm, a consistent system data model is implemented in VirSat which also supports calculation and perform analysis [5]. The Version Control System (VCS) is used to provide a data repository for recording evolving versions of spacecraft designs. The data model supports hierarchical tree-like decomposition of the studied system which makes it much more efficient for changes by individual domain experts. And eventually, its model transformation mechanism supports to convert the configuration data into a format suitable for visualization [6].

Because of the iterative Concurrent Engineering (CE) process, many versions of a configuration design evolve over time. Those quantities are usually depicted only as text information. And furthermore, one system usually consists of many versions and many subsystems. Thus, it can become very tedious, unclear, and time consuming to check the text items of every subsystem of every version just to find differences of interest.

To get a better insight into the history of decision making, stakeholders and engineers need to get an intuitive tool for a clear understanding of how a system evolved and for a direct comparison between different versions of the spacecraft configuration. If needed, the current design may be refused and a different version may be selected. Or based on the history, design decisions might be approved. To support this, appropriate methods have to be offered to display

different versions of space systems clearly and to give experts a better and intuitively perception of the differences between different versions for all key configuration information such as geometry, mass, temperature, and power consumption.

Therefore, the VirSat implements 3D visualization for a quick survey of configurations. It can also be connected to Virtual Reality (VR) visualization environment where experts can demonstrate and discuss design issues during the development progress [7, 8]. To solve the manual data mining problem mentioned above, we have extended the VirSat for graphical comparison approaches. Now, the difference in parameter values between versions are extracted and computed automatically, before they are displayed by means of 3D visualization or VR technologies. This creates a quick and intuitive insight into complex interdependencies.

This paper starts with an introduction of state of art in computing design differences and how to present different versions of models. Then, it depicts approaches of commercial CAD software packages to compare design evolutions. Thereafter, the VirSat architecture, the versions control system, and the system data model is described. Also the implementation of the visualization in 3D and VR is explained. The strategies to compare different design versions graphically are demonstrated. And their visualization results and their advantages are presented and discussed. Finally, we summarize our work and give some outlook to future work.

RELATED WORK

Computation and Presentation of Differences

Version control systems such as Subversion and Git are frequently used for versioning of software development projects. Besides submitting and updating source code files, those tools also allow for comparing differences between several versions of documents. A large number of comparison algorithms have been proposed which can be distinguished between approaches for textual and structural documents. Structural documents record models which have graph-like or tree-like data organization. This is for particular interest for VirSat. Its system model uses a tree structure to map system, subsystem, equipment, and parameters in an adequate way. Therefore, we focus on structural model comparison in the subsequent paragraphs.

The evolution or branching of a structural model can lead to a situation where certain versions may not be comparable anymore in a straightforward way. Thus, relations between branches and components have to be computed [9]. We can distinguish between two classes of algorithms in order to extract the parts to be compared: similarity-based and identifier-based methods. Similarity-based algorithms compare all pairs of elements of the two models and can often be applied to ordered or unordered trees (e.g. when using XDiff and SiDiff) [9]. For the organization of 3D scenarios, optimized scene graphs are used. For those, Berthelot et al. showed in [10] that relations of corresponding parts can already be established in the underlying data structure. A flexible tree matching algorithm has been presented by Kumar et al. which finds corresponding tree nodes despite different descendants [11].

Many tools are based on persistent identifiers, which help to specify relations between model elements. This approach belongs to the family of identifier-based algorithms. Two model elements are determined as corresponding if they have the same identifier. This approach is very efficient. As similarity-based algorithms sometimes yield wrong results [12], VirSat also relies on an identifier-based algorithm which uses assigned ID values as depicted in [13].

Besides identifying differences, they have to be presented to the user as well. The presentation of textual changes in a line-by-line fashion works well for textual document. For structured data, Gleicher et al. identified three main strategies for visualizing differences: juxtaposition (side-by-side), superposition (overlay), and explicit encodings (time warp or subtractions) [14]. Superposition is known to be superior for cases where clearly structured data such as trees and 3D geometry models are utilized [15]. Therefore, we also prefer superposition for the approaches depicted in this paper to display the differences between two versions of satellite configurations.

Version Comparison in other Professional CAD Software

Most of the commercial CAD software packages offer functionalities to support engineers to identify and understand differences between several versions. However, these tools are tied to proprietary models and their used algorithms are unknown [12]. One example is CATIA, which is widely used for system design in the aerospace domain. It provides means for part and product design comparison [16]. A Visual Comparison viewer shows the differences indicated by different colors: yellow indicates common material, red indicates added material, and green indicates removed material. SolidWorks also supports version comparison, and differences between two versions of a design are shown graphically as well [17]. When comparing the geometry of two versions, the added material, removed material, and common material are indicated with different colors and can be displayed separately. Another tool is KeyCreator Compare,

which is integrated as a standard feature into KeyCreator Direct CAD [18]. It supports many file formats produced by other CAD software, and also indicates geometrical modifications between versions by red and green colors.

To sum up, version comparison functions have been applied in most CAD software. In most cases, the geometrical differences are indicated graphically with special colors. Comparison of some other features rather than geometry is rarely available. The VirSat system model, however, also supports studies of other parameters such as mass, temperature, power etc. Therefore, the VirSat is in the position to consider those key performance indicators of satellite systems for visualization purpose as well in order to leverage an understanding of interdependencies in a design. Color map can be adjusted to demonstrate the value distribution of such indicators (e.g. mass). Comparison result of these features is also displayed graphically. We have adopted the overlay visualization approach for differences between satellite configuration versions. This is more of practical use and can avoid the problem of attention dispersion which happens often with the side by side comparison approach. Besides, an animation mode, rarely used in other CAD software, is additionally implemented in VirSat. The animation approach displays design versions from old to new continually giving designers an intuitive comprehension of the product design progress.

Virtual Satellite

As a standard tool for concurrent engineering studies at DLR, Virtual Satellite supports domain experts and engineers to simplify the satellite design process and organize the data conveniently. Each domain expert runs an instance of VirSat on his/her individual workstation and works locally on a copy of the data model [7]. Experts are only allowed to alter components if they have sufficient permissions. VirSat uses Subversion (SVN) as a Version Control System (VCS) to manage and exchange evolving versions of the satellite design data.

A consistent system data model based on MBSE is implemented in VirSat which supports hierarchical tree-like decomposition of the space system for building an effective data base. Experts can create system, subsystems, components, and equipment hierarchically. As shown in Fig.1, a geometric model can be attached to an equipment to describe its shape, size, position, rotation etc. This model can be transferred into a visualization model and rendered in a 3D visualization window of VirSat. This view is based on the Visualization Toolkit (VTK) which includes a wrapper for Java and makes it easy to be integrated in VirSat [19]. Other satellite configuration parameters such as mass, power consumption, and temperature can also be flexibly attached to each component and equipment. The visualization of these parameters can help engineers to get a clear, quick and comprehensive insight into the current design status.
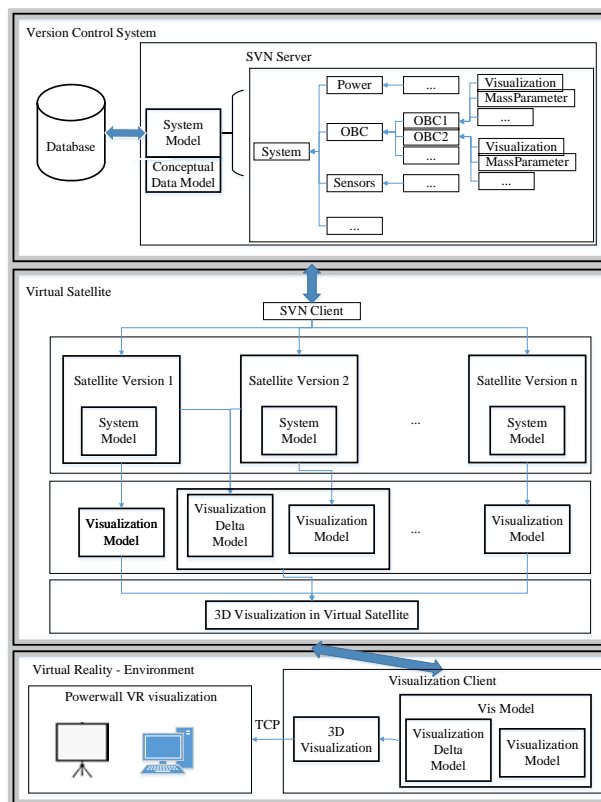

Fig. 1. Architecture of Virtual Satellite for Comparison Visualization

Additionally, VirSat can be connected to VR environments for immersive visualization and interaction. The VR implementation is based on the VR Toolkit ViSTA [20]. The messages between VirSat and the virtual environment are transferred across the network using the Transmission Control Protocol (TCP).

VERSION COMPARISON IN VIRTUAL SATELLITE

We implemented comparison of geometry and important parameters such as mass, power consumption and temperature between the different versions in VirSat. For giving engineers more intuitive understanding of the differences, VirSat visualizes the differences in the visualization view in VirSat as well as in a VR environment. The comparison between versions can bring many benefits. For stakeholders, they can grasp the project progress more explicitly. For experts, inevitably they could make some mistakes, make some changes unnecessarily or make some decision turns out to be wrong. Experts can learn lessons from the old versions and from the comparison between evolving versions. They can also develop a new system based on older versions or other similar systems.

As showed in Fig.1, engineers can load several versions of spacecraft configuration design in one workspace of VirSat for version comparison. We use Universal Unique Identifier (UUID) for each component so that the same parts of a model can be matched when comparing models' different revisions.

In the next sections, we explain the comparison strategy and implementation of version comparison of geometry, version comparison of parameters, color map for parameters and the animation mode for version comparison.

Data Model for Comparison Visualization

As showed in Fig.1, each version of space system design has its own visualization scene graph model for visualization. When we visualize the differences between versions, it is important not to damage the integrity of the visualization scene graph model for every version. To achieve this, we create Visualization Delta Model (VDM) for version comparison visualization. When we compare design from two versions, we generate a new VDM file to describe the difference. The VDM contains a similar scene graph compared to the actual visualization model and can be fused into this visualization scene graph model.

Version Comparison of Geometry

As described before, geometrical information of a component can be attached in VirSat. Values of this component get transferred into a node for the visualization scene graph. The visualization data model follows a hierarchical tree-like structure. Position and rotation of the parent node are inherited by its child nodes. So when we compare two versions of a geometry element, we also should compare their parents' and ancestors' geometry position and rotation. The geometry model element is identified by its parent equipment's UUID. If two geometry elements from different versions have the same UUID, their values will be compared.

Four kinds of comparison possibilities between two versions of geometry are defined: something has been added, something has been removed, something is unchanged and something has been modified. Highlighting the selected version of satellite design using different colors in one window is useful to indicate the comparison results. Particularly, we still visualize the removed equipment in special color thus we can get comprehensive information. To avoid confusion caused by too many kinds of color indicators, the detailed changes in the geometry like position or shape changes are not visualized in a special color. These changes can be checked in the corresponding equipment data.

Version Comparison of Parameter

VirSat supports attaching parameters to system data model for each equipment part to describe its different features such as mass, power consumption and temperature etc. Version comparison should support these parameters which play an important role in satellite configuration. For example, the mass of satellite have restriction due to launch vehicle's capacity. Also the mass distribution affects satellite's center of gravity. Temperature parameter is also crucial due to positioning of equipment based on its thermal constrains. The comparison and visualization of important parameters can improve communication between the engineers, support making decisions and lead to better design choices. The parameter model is also identified by its parent equipment's UUID. We compare two versions of parameter whose parent equipment have the same UUID.

There are five kinds of comparison possibilities: something has been added, something has been removed, something is unchanged, some values have been increased and decreased. We also use different colors to indicate the comparison results.

Color Map of Parameter

Color map is a technique we use to visualize values of one specific parameter like mass across every component of the satellite in different colors. This is useful to compare components' values in relation to one specific parameter.

Color map for parameter can give engineers more intuitive perception for important feature of satellite configuration. For example, previously we use table to display the mass distribution of satellite subsystems [2]. If we want to get detail information of equipment, we should check the subsystem in the system model and find the equipment data. With color map view, experts get overview of mass distribution of every component along with positioning in a spacecraft in one view. Engineers can choose specific parameter they want to color map by choosing a specific version of the system and enable color map. Then VirSat extracts the parameter's value of every component and get the max and minimal value to define the range. These values of every component are mapped to a specific color in a defined color spectrum. This spectrum ranges from blue to green then to red, correspondingly the value changes from the minimum to maximum. The geometry date of equipment with same UUID with parameter's parent equipment is visualized with the mapped color to indicate the parameter. If the parameter value from one component is not defined, this component will be colored in grey. This can remind engineers to add parameter to the equipment.

Animation Mode for Version Comparison

Animation mode displays the comparison results between adjacent versions continuously from old version to new version. This gives us a clear presentation of the satellite configuration design progress. Engineers can choose several versions of satellite system in workspace of VirSat for animation. The differences between versions have been emphasized so that engineers can easily grasp the development progress.

EVALUATION OF VERSION COMPARISON IN VIRTUAL SATELLITE

This section explains the actual results generated in VirSat using AHAB (Atmospheric High Altitude proBe) mission data as an use case [8]. The Data Set showed in the following figures is created by students to replay the scenario of project AHAB.

Fig.2 shows the interface of VirSat to help configuration of Satellite. On the left side is VirSat navigator in which multiple versions of the same project can be opened and displayed. With right mouse button click of one version, there will be a menu popping out listing the items for comparison operation. In every version, the data set of satellite configuration is organized in tree like structure. On the right side is a textual editor in which engineers can edit the value of certain configuration parameters. In the middle is a 3D visualization viewer to display the currently selected satellite configuration version. The operations such as Geometry Compare, Parameter Compare, and Color Map generate visualization delta model files which are used for visualization. By selecting the visualization delta model file, the viewer displays the corresponding comparison results.
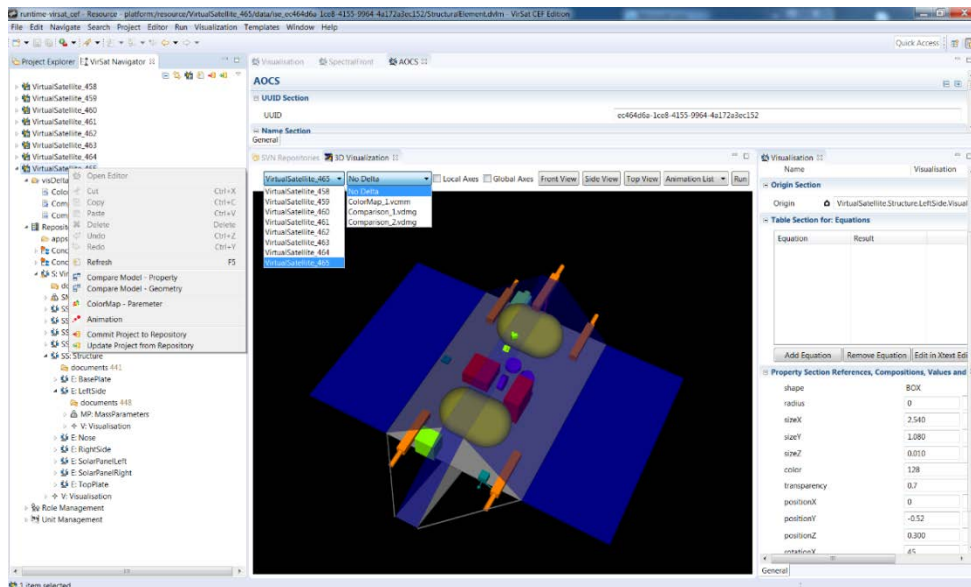

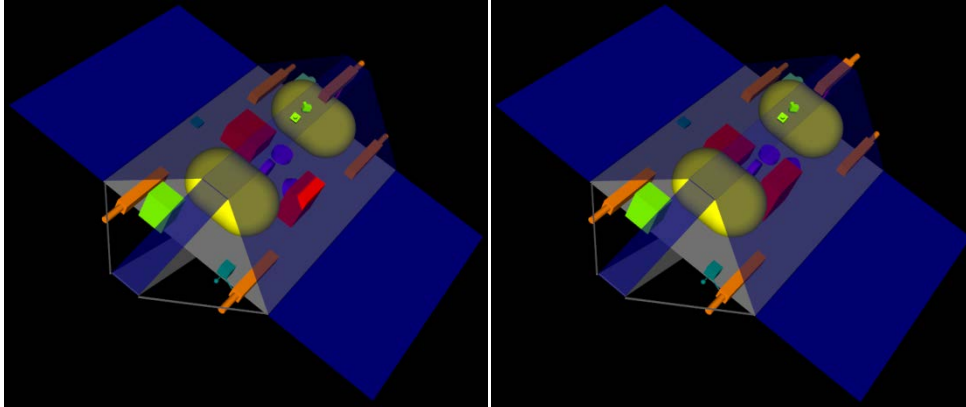Fig. 2. The software Virtual Satellite Interface for Satellite Configuration

Fig. 3. Satellite model version 464 and 465

Fig.3 shows the visualization for two versions of AHAB design in VirSat. There are many kinds of equipment in Satellite model. We can hardly find the differences between these two versions with naked eyes from the pictures. It's also tedious to search for the difference by checking the data parameters. VirSat visualizes these differences with emphasized effect to help experts in finding the changes easily. Then experts could check the details and decide which kind of changes should be kept and which should be discarded.

Fig.4 shows the geometry comparison results between two versions of AHAB model. The geometry data describes the shape, size, position of equipment in the satellite model. Compare to Fig.3 we can easily view the changed information from this picture. The grey components are the unchanged equipment including fuel tank, solar panel etc. The red equipment is a newly added on board computer in new version. The green component is a removed computer which represents it only existed in old version but has been deleted in new version. The blue components are equipment whose geometry parameters have been modified including 3 thrusters, a computer and a reaction wheel.

Fig.5 shows comparison results of the mass parameter between two versions of AHAB model. Visualization of parameters comparison is important but did not get enough attention in most of the CAD software. We can easily understand the changed information from Fig.5. The grey components are the equipment including solar panels, fuel tanks etc. whose mass parameters are unchanged. The red components (e.g., top plate, computer, thruster etc.) represent addition of a mass parameter in a new version. The green colored sensor Langmuir represents its mass parameter has been removed in new version. The blue colored nose plate represents its mass parameter value has been modified to the higher value, while the cyan colored poles represents their mass parameter values have been modified to the lower values.
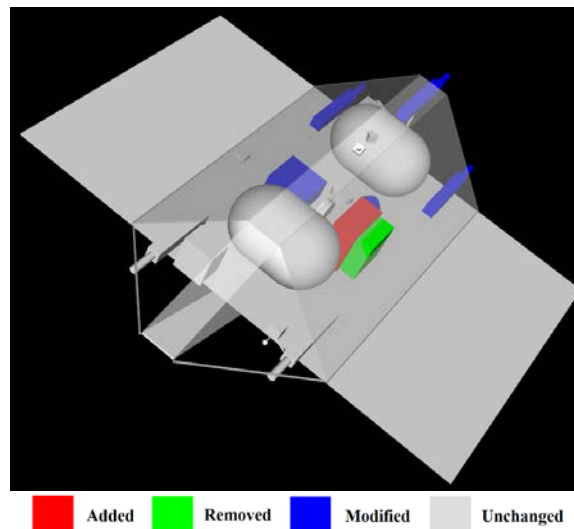

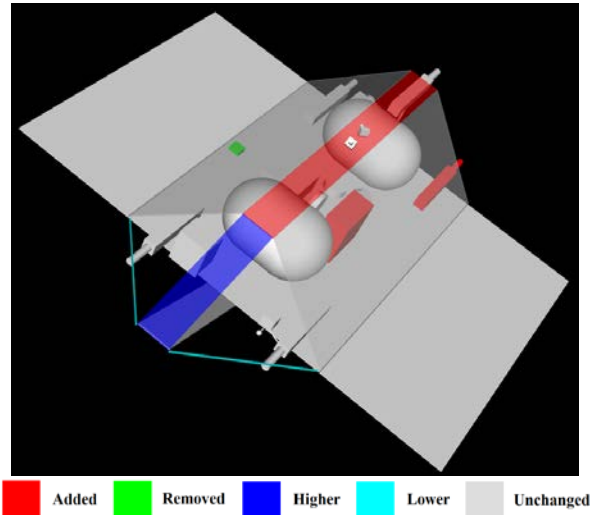Fig. 4. Geometry Comparison results of version 464 and 465

Fig. 5. Mass Parameter Comparison results of version 464 and 465

Fig.6 shows color map results of the mass parameter for AHAB design of one version. Color map visualization of parameters can give experts an overall perception of specific indicator information such as the mass distribution in Fig.6. From the diagram we can see the range of mass distribution through satellite and rough mass value with the corresponding color. With the increasing mass value, the color of equipment changes from blue to green then to red. The blue component indicates the corresponding equipment including the sensor Langmuir and reaction wheels has minimal mass value. The red component indicates the corresponding equipment fuel tanks have maximum mass value.
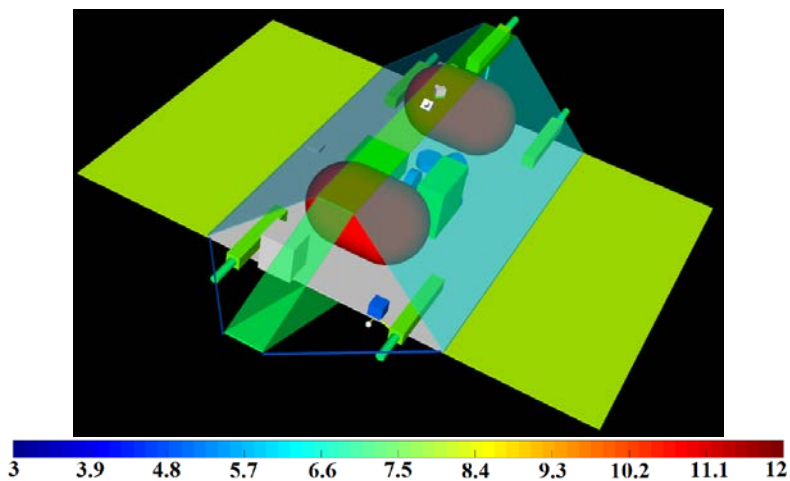

Fig. 6. Mass Color Map results of Satellite model version 465

Animation mode is showed in Fig.7. There are five frames to show the design progress from version 462 to version 465. The first frame is the visualization of version 462 while the last frame is the visualization of version 465. Other frames show the differences of the current version comparing with previous version. For example, second frame shows the difference between version 463 to version 462 which is indicated by the red color box. It represents there is a new spectral sensor added in version 463 comparing with version 462. In this way, the design progress is displayed.
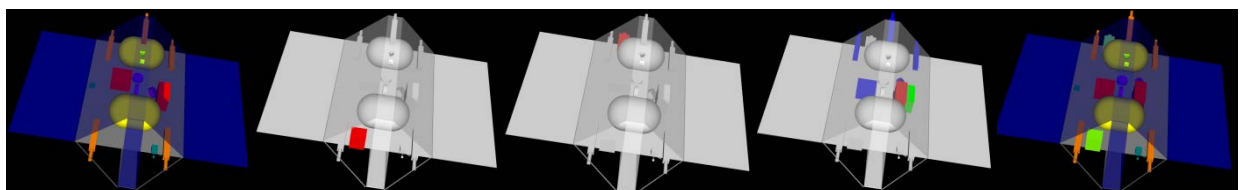

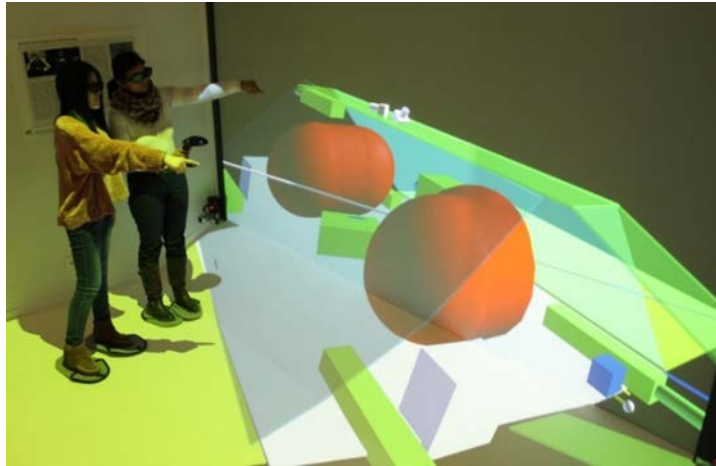Fig. 7. Frames of Animation mode from version 462 to version 465

Fig. 8. Mass Color Map results of Satellite model version 465 in VR environment

All the visualization style above can be visualized in VR environment. Fig.8 shows the visualization for color map results of mass parameter for satellite design version 465 in VR environment. VR immersive environments typically offer a stereo view with a dynamic, first-person viewing perspective for the user. In immersive environment, engineers consciously and subconsciously use their body in a natural way thus improving the communication for collaborative work. For example, engineers can simply point at objects with their hand instead of thinking about how to use a specific interaction device.

CONCLUSION AND OUTLOOK

As introduced, many versions of spacecraft configurations are designed and development in CE studies and are evolving over time. Keeping track of these various different versions and instantly spotting their changes is not an easy task but required by the engineers for proper decision making. As described, textual or table based comparison of parameters is possible but still not enabling intuitive, fast and proper decision making as well. As a consequence, the work described in this paper shows the effort of using computer visualization and VR to improve the situation of design comparison.

By today, the aforementioned version comparison is not new and has been applied in most of the CAD software. In most cases, geometrical differences are indicated graphically by color coding changed, deleted or added components. However comparison of other features such as mass is rarely visualized.

The implementations of this work are based on the software Virtual Satellite which is DLR's standard tool to support concurrent engineering studies in the CEF. Up till now it was possible to visually display configurations during the studies, both in the desktop software itself or in dedicated VR environments.

This functionality has been extended to enable comparison of designs during the study. As a baseline, similar to professional CAD software, users can now compare two different designs on geometric basis. This provides an intuitive access to changes such as moved, resized, deleted or added equipment in the design. The second approach goes beyond pure geometric comparison, and lets the engineers compare two designs on a specific property of the design such as component masses. This provides intuitive insight to which equipment got heavier or lighter. The third implementation also focuses on specific system properties but it does not compare them to another configuration. It creates a color map which is overlaid to all system components of one data set and colors the individual components depending on the actual value of the inspected property. This means the engineers can use the functionality to intuitively spot design drivers, e.g. by easily identifying the lightest and heaviest component of a spacecraft. The last implementation creates an animation of changes from multiple data sets introducing a time component into the analysis. This functionality allows reflecting past decisions before deciding on the next steps.

Due to the technical implementation, the comparison is performed before actually visualizing it. Detected changes from the comparison algorithms are persisted into a so called Delta Model. This model describes the differences of data sets. When visualizing a spacecraft configuration, such a Delta Model can be selected by the user and overlaid to it. The underlying scene-graph is changed accordingly and transmitted to all visualization clients showing these differences. This applies to connected VR environments as well. Finally, they offer a much more immersive sensation compared to the desktop visualization, to first experience the current design and second to spot differences in the comparison.

As future work it is considered to extend the here explained approach. In particular the VR environments promise new ways of interacting with the modelled data. Further research will be needed to investigate the full potential of future

applications in particular in combination of emerging trends such as head mounted VR displays. As one of the dominant examples, the Microsoft HoloLens may improve design discussions during CE studies and could also be used in connection of spacecraft configurations during later projects phases such as in Assembly Integration and Test (AIT).

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