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Název tématu: **Interaktivní model tokamaku GOLEM**

Pokyny pro vypracování:

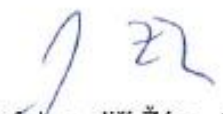
Sestavte virtuální model unikátního laboratorního přístroje pro termojaderné slučování zvaného tokamak. Vymodelujte všechny jeho části - hlavní laboratoř, kondenzátorovnu, velín a samotný vnitřek komory. Uživatel modelu bude mít možnost procházet všemi místnostmi, zjišťovat funkce jednotlivých součástí a vstupovat i do fyzicky nedostupných míst (vnitřek komory, apod.). V dlouhodobém horizontu bude mít uživatel možnost provozovat tokamak virtuálně a vidět jej a jeho funkce ve virtuálním provozu.

Seznam odborné literatury:

Webové stránky tokamaku GOLEM na FJFI ČVUT: <http://fusionexpo.fjfi.cvut.cz/?q=virtualne>

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Bakalářská práce

Interaktivní model tokamaku Golem

Bachelor's Thesis

Interactive model of tokamak Golem

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Vedoucí práce: prof. Ing. Jiří Žára, CSc.

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Prohlášení

Prohlašuji, že jsem svou bakalářskou práci vypracoval samostatně a použil jsem pouze podklady uvedené v příloženém seznamu.

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Abstract

Tokamak Golem is a useful piece of laboratory equipment on the grounds of Faculty of Nuclear Sciences and Physical Engineering of Czech Technical University in Prague. The main aim of this project is to create an interactive virtual world with tokamak Golem inside accessible online for public. This virtual world contains rich information of the tokamak from its visual appearance to basic functionality. Tokamak Golem has not been transferred into virtual environment before; therefore this project will be a great asset to students and professors in learning how the device works even before they go hands-on with the actual equipment. Virtual Reality Modeling Language (VRML) was used as a project requirement.

Abstrakt

Tokamak Golem je unikátní zařízení, které se nachází na Českém vysokém učení technickém v Praze, konkrétně na Fakultě jaderné a fyzikálně inženýrské. Hlavní zaměření této práce je na vytvoření interaktivního virtuálního světa s tokamakem Golem uvnitř, který bude přístupný veřejnosti online. Tento virtuální svět je první svého druhu a obsahuje množství informací o zařízení a jeho funkcionalitě. Virtuální tokamak Golem pomůže studentům pochopit složité zařízení tokamak ještě před tím, než opravdový tokamak uvidí ve skutečnosti. Virtual Reality Modeling Language (VRML) byl použit pro vytvoření modelu scény.

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Chapter 1

Background

Today, energy demand is of the world's concerns. The total amount of non-renewable resources is depleting. One of the possible solutions for energy crisis is by harvesting energy extracted from nuclear fusion. This makes nuclear fusion reactor, a tokamak based device extremely crucial in creating this form of energy. Most of the people who are not nuclear science-specialized do not know what exactly tokamaks are and what their purpose is. This chapter provides a basic overview of tokamaks. The information presented here is fundamental for better understanding of this project.

1.1 History and future of tokamaks

The word tokamak is an acronym from a Russian word “**toroidalnaya kamera v magnitnykh katushках** (toroidal chamber with magnetic coils). The first tokamak was made in Russia approximately 50 years ago. Around 1920 physicists began to think about nuclear fusion as a source of energy for the future [1]. The technology back then did not permit it. After the Second World War in 1946 a patent was filed for the first fusion reactor. It had a basic structure of today's tokamaks. Countries which were interested in thermonuclear fusion in 1950s were the USA, GB and Russia. They kept their research secret because of its high potential in weaponry. France, Germany and Japan joined the fusion research in 1955 when it was declassified and brought to wider public. In 1958 a conference in Geneva, Atoms of Peace was held. Participating countries shared the technology and experience with nuclear fusion and a formal international collaboration started. Tokamaks were invented shortly after the conference. In 1968, the first success of tokamak device was announced. Russian scientists reached temperature over 1000eV which is approximately $1000 * 11604 = 11\ 604\ 000\ K$ on tokamak T-3. [2].

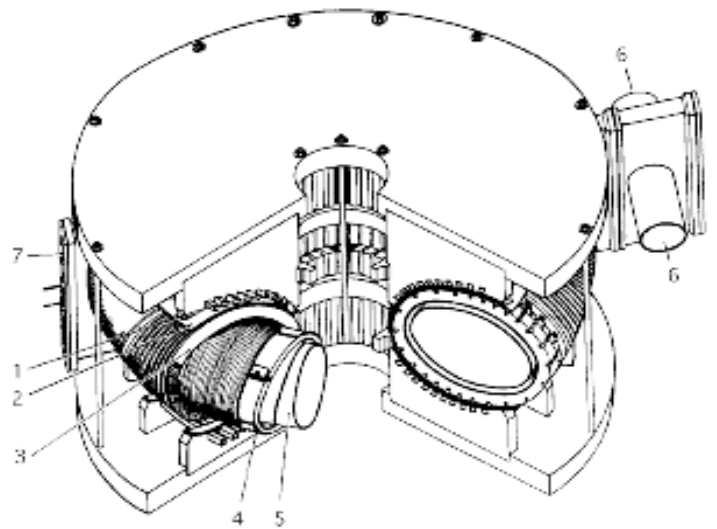


Figure 1 - Diagram of the Kurchatov Institute's T1 tokamak in Moscow [1]

Tokamaks clearly became the most important tool for research of thermonuclear fusion. Many tokamaks have been built since then. There are around 50 working tokamaks nowadays. [3]

The current on-going project of the modern version of tokamak is International Thermonuclear Experimental Reactor, (ITER). Countries collaborating on the project are China, India, Japan, South Korea, the EU and the USA. ITER will be the biggest and the most advanced tokamak. ITER project which costs over 10 billion Euros is one of the most expensive projects in the related area ever. Scientists will use ITER to collect data necessary for construction of functional power plant in the future. Tentatively, it will be launched in 2018. DEMO, the first power plant of a kind should be built upon the success of ITER project. It should be a fully functional thermonuclear fusion power plant. DEMO could be launched in 2033 if everything goes according to the plan. [4]

1.2 Thermonuclear fusion

Tokamak is a device which simulates the same conditions as are in the stars and under these conditions thermonuclear reaction can occur. The simplest thermonuclear fusion is the fusion of two isotopes of hydrogen (deuterium and tritium) nuclei to helium. Sun needs 4 nuclei of hydrogen but for tokamak fuel, isotopes are more practical. High energy nuclei have to collide to fuse. The nuclei need to overcome an electrostatic barrier where equally (the same electric charge either positive or negative) charged particles repulse each other. This can happen only when the temperature/pressure is extremely high.

Thermonuclear fusion runs nonstop in cores of stars. The light we see coming from Sun is a product of nuclear fusion inside the core. When nuclei of lighter elements fuse into nuclei of heavier elements, the energy within is radiated out of the matter.

In high temperature plasma science research, scientists are trying to produce energy from nuclear fusion. The overall weight of the material entering the reaction is higher than the outgoing one. According to the Einstein's formula $E=\Delta mc^2$ (energy released is equal to mass decrement multiplied by the square of speed of light), energy hidden in the fusing matter structure is released when the mass decreases. It is very difficult to simulate the same conditions as are in the stars on Earth. Tremendous gravity in cores of stars creates huge pressure on material inside. Temperature of 15 000 000°C is reached because of molecule/atom friction (and increased pressure due to increased density) and nuclei of hydrogen can fuse. The temperature 15 000 000°C is valid for Sun but different stars have different conditions inside their core and therefore the temperature needed for the fusion will vary.

1.3 Tokamak

Tokamak is an experimental device used in the field of thermonuclear fusion research. It works on the principle of creating plasma, heating it up and maintaining in the magnetically confined environment. The main part of the tokamak is a doughnut-like vacuum chamber. This chamber is used to confine extremely hot plasma with the help of the strong magnetic field of several Tesla, created in toroidal magnetic field coils to keep the plasma from being in the direct contact with the chamber. If the fuel inside touched the walls of the chamber it would burn through.

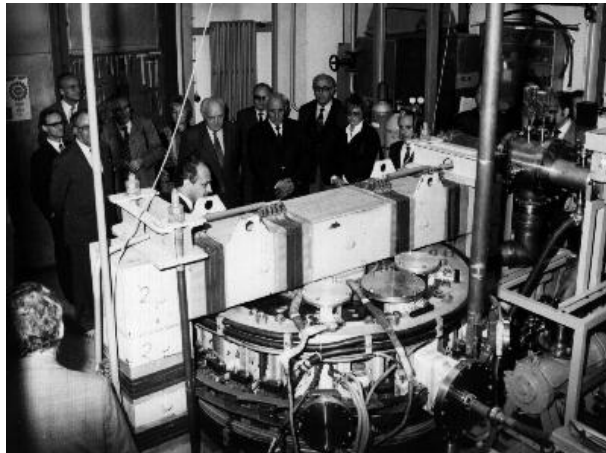


Figure 2 - Start of operation of tokamak Castor [5]

For heating up the plasma, an omnic heating technique is widely used. Plasma is hot and electrically charged gas and thus it is an excellent electric conductor. Electric current in the plasma heats up plasma the same as it would do to any resistor. Electromagnetic induction via transformer core is used to induce the necessary toroidal electric field. Additional heating systems are used when omnic heating is not sufficient. Tokamaks are very complex devices and they need specially trained people to work with them and maintain them.

Tokamak is fueled by deuterium and tritium mixture. These are isotopes of Hydrogen which are the most optimal fuel. They radiate the biggest amount of energy in the lowest possible temperature needed for their fusion. Nonetheless, temperature required is still as high as 100 million degree of Celsius.

1.4 Tokamak GOLEM

Tokamak Golem is the oldest and smallest tokamak still being used. It was built in Kurchatov Institute of Nuclear Research in Russia in 1959. The original name of the tokamak was TM – 1. In 1977 Czechoslovakia was given the tokamak by The Union of Soviet Socialist Republics. TM – 1 changed its location for the first time. The new name was CASTOR as Czech Academy of Science Torus. [5]. Tokamak CASTOR was completely rebuilt shortly after it was received by Czechoslovakia at the Institute of Plasma Physics in Prague. They have been using CASTOR since then until 2006. In 2006, it was moved to Faculty of Nuclear Sciences and Physical Engineering of Czech Technical University. Tokamak Castor was renamed to Golem. Golem is now used for educational purposes.

Parameter	Tokamak Golem	Tokamak ITER
Minor radius of toroidal chamber (meter)	0.1	3
Major radius of toroidal chamber (meter)	0.4	9.5
Height of tokamak (meter)	Less than 2	Over 11
Toroidal magnetic field (Tesla)	0.8	13
Weight of the vacuum chamber (ton)	1	5000
Reachable temperature inside the chamber (million °Celsius)	$X < 2$	$X > 150$

Table 1 - Comparison of tokamak Golem and tokamak ITER [6] [4]

Chapter 2

Introduction

In this chapter an overview of the whole project will be reviewed with its challenges and problems.

2.1 Criteria of the thesis

Originally there were three rooms (tokamak room, infrastructure room and control room) with all the equipment to be made. All the functions of the real device should be reflected in the 3D model. The model was to be created in a game-like environment and users should have access everywhere in the scene. The model should be optimally operable online.

The original requirements were modified during the process of writing the thesis. The main goal of this project is to construct a model of tokamak Golem. Infrastructure room was created by Petr Liška and inserted into the scene. Control room is replaced by accessing webpages from where the real Golem can be controlled. The focus of the project is mainly on the tokamak device. Users should freely walk in the virtual environment and explore the model. All the places in the scene should be accessible including the vacuum vessel. These functions implemented should help users to learn about the tokamak but don't have to reflect the real functions. Virtual technical operation of tokamak was omitted and can be considered as a future improvement. In general the project should preferably serve as an educational tool rather than exact simulation.

2.2 Current situation of Golem

Tokamak Golem (Figure 3) is located in a very small room at Faculty of Nuclear Sciences and Physical Engineering (FNSPE). Not everyone can operate and control the device. Every experiment on the tokamak requires unique knowledge of the given problem and different handling of the tokamak itself. There are experiments that could endanger people working with the tokamak and/or destroy the laboratory equipment. Some parts of the device can be even dangerous when touched during experiments. Conditions inside the device are extreme and if the insulation failed it could result in severe consequences. The infrastructure room directly under the tokamak room plays an important role for proper functioning of Golem. It is equipped with power distribution system for tokamak. Tokamak's power consumption during experiments is very high. Any device which works with high voltage as tokamak does is potentially dangerous. Although Golem can be controlled online from distant computers over the internet, sometimes it is necessary to come inside the tokamak room for close observation and controlling.

There are many students coming from Czech Republic as well as abroad to work with the device. They usually have very limited time

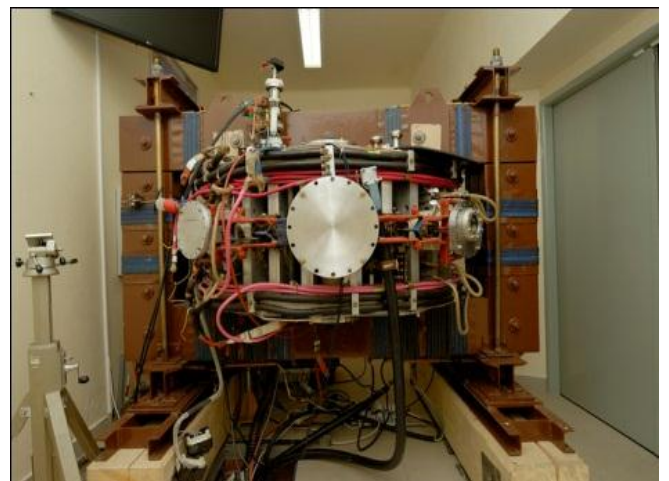


Figure 3 - Tokamak Golem inside the room [6]

for their experiments. It is a difficult job for professors to explain various functions of different parts of Golem in a short time frame.

2.3 Importance of good information on Golem

There is a lack of accessible information on tokamak Golem online. Students have to know the device before they conduct any experiment. A big portion of the students working with the tokamak are foreign incoming students on short-term studies. They especially need to have access to good and understandable information of Golem and its functions. Professors face the other side of the same issue. They require students to master the functions of tokamak. If students are not able to perform adequately with the device they cannot proceed with any experiments. Valuable time is lost when professors have to explain everything repeatedly with every new group of incoming students. The resources of Golem accessible online for students are limited.

If students can learn basic operational principles with tokamak and be familiar with the environment in advance, they will be faster and more effective doing the experiments. Professors will not have to give extra lessons. Working in a team is also much easier if everybody has the same minimal background knowledge. Good knowledge of the device is a must for the students to work with Golem successfully and without mistakes. Students will feel better and more confident during the experiments if they are informed about the functions of the device beforehand. This project can also help to promote the school for its effort in producing 3D interactive educational materials for Golem.

Tokamak Golem has its websites full of pictures and information which are well organized. The problem lies on the fact that none of them are descriptive enough. Students or general public can learn basic historical and technical facts but it is impossible to find an easy-to-understand manual for Golem.

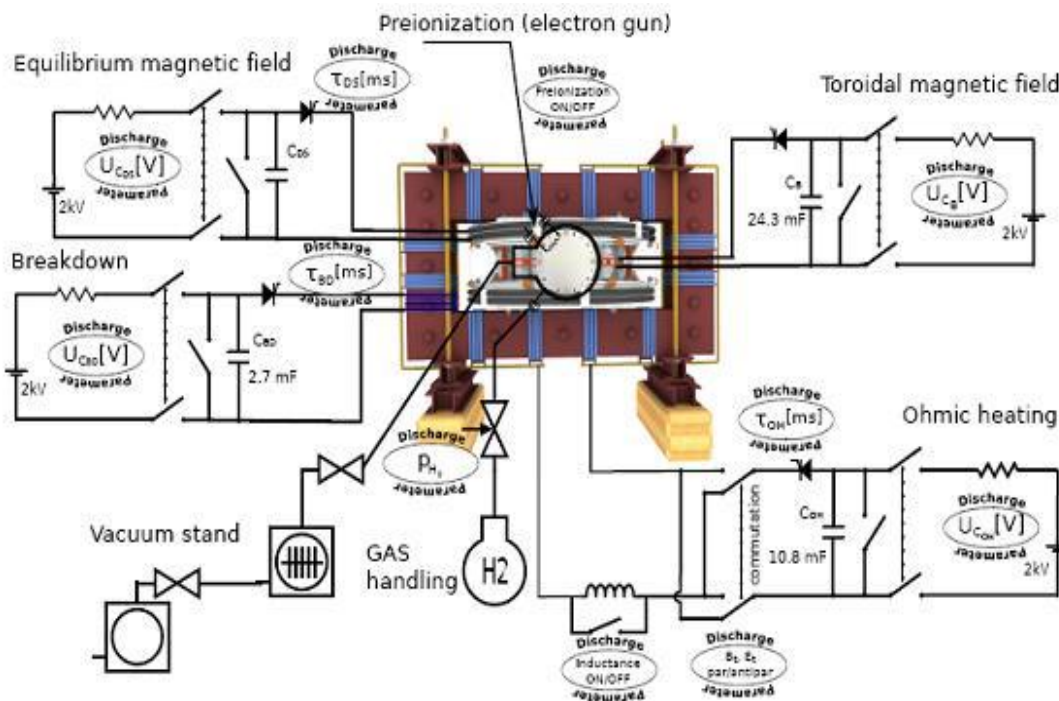


Figure 4 - Engineering scheme of tokamak Golem – picture original work; electronics scheme courtesy of [6]

2.4 Virtual 3D world solution

To deliver complex and comprehensive information about tokamak Golem to students over the internet is a difficult task. The information must be understandable and clear. It also needs to contain a huge amount of visual data because the device has many different parts. Pictures could be normally used for simple description of the device. The problem of these static pictures is they carry limited information at once. A lot of photos from different angles and distances are needed to model the tokamak. Pictures cannot be easily united into a teaching tool. Thus, only a videogame-like environment with 3D reproduction of the tokamak device is the solution to using static pictures issue to effectively transmit the necessary information to students. It is noteworthy that memory demands for the virtual world should be low enough to make the world accessible online without sacrificing its quality. 3D virtual interactive manual is a good teaching material as it is the closest imitation of the reality.

Creating an immersive reality is a complex matter. Not only the visual side of the model has to correspond with the reality but it must be interactive and explanatory. It has to fulfill the purpose of being used as a teaching tool and learning material. 3D model of tokamak Golem has to be detailed and look-alike with its features in reality. Interactivity of the model should be smart and natural. As the 3D virtual world is to be placed online, the size of the files should be less than a several megabytes. Students have to be able to access the virtual model from their computers at home. It means that the virtual world has to play fluently even on average computers.

2.5 VRML over X3D

Both Virtual Reality Modeling Language (VRML) and Extensible 3D (X3D) are programming languages used for creating and displaying of 3D graphics on the internet. They are two optimal choices for creating virtual reality online. X3D is considered as the successor of older VRML. It introduces new features and adds support for Extensible Markup Language (XML) encoding. Logically X3D should be a better choice to pick since the functionality is more comprehensive and it is newer than VRML [7]. However, there are a few reasons why VRML is a better pick for this project. More people are familiar with older VRML than newer X3D. Since this project is to be extended in the future it is important for future modelers to know the project's programming language. X3D is basically an extended version of VRML therefore it is easy to transform project files from VRML to X3D if necessary. VRML has still larger support online. There are more VRML browsers than that of X3D. 3Ds Max modeling software used later in this project has built-in exporter to VRML which except ordinary geometry can export animations and recognize basic primitives which is important for the project. There is no X3D build-in exporter in 3Ds Max and other downloadable exporters are mostly under development. VRML is also preferred by professors at the author's university because it is still actively taught to students.

More details about VRML are described in later chapters when the model is optimized directly in VRML.

2.6 Challenges

Availability of data necessary for reconstruction; Golem does not have any accessible construction plans. It is a very old device and proper documentation in a good form does not exist. Transferring the existing object into virtual environment under these constraints is complicated. Proportions of the model must remain and in general the model has to be realistic and believable. Since there are no materials to suggest the size and exact shape of multiple parts of tokamak, they need to be discovered differently. Exact measurements of all the parts of tokamak are not possible because the parts are assembled together. Some of them are not even visible.

Modeling of Golem; Precision of the location of each part and its size is important. The whole model of tokamak Golem contains hundreds components. Only the most basic parts are constructed because such level of detail is sufficient for learning purposes. These pieces can overlap unnaturally in the

virtual environment. It could make the model unrealistic and useless as a convincing copy of the real tokamak.

Data optimization; Model is to be placed online. The Internet has some limitations that need to be complied with. Crucial is the file size. It needs to be as small as possible. Optimally it should be less than a few megabytes.

Internal structure; Programing structure of the 3D model in VRML should be well organized and be flexible for future expansion.

Educational tool; The project must be useful as an educational instrument. The interface should be kept simple and understandable even for common users who are not computer savvy.

2.7 How to use the model of tokamak

The virtual scene must be run with computers of at least the following minimum requirements and with installed VRML viewer. VRML viewers are applications usually downloadable from the internet for free. They are applications which can open and play VRML files. There are many VRML viewers online but the scene of tokamak Golem was tested only with the following two:

Computer minimum requirements

- Intel (R) Core(TM) 2 Duo CPU T7300 2x2GHz
- RAM 2GB
- Mobile Intel(R)965 Express Chipset Family - graphic memory (RAM 358MB)

VRML viewers

- Cortona 3D – very powerful viewer for VRML [8]
- BS Contact – fast viewer with a lot of functions [9]

The main file of the virtual scene **tokamakGolem.wrl** located on the included CD can now be opened by the viewer. The default settings of the viewer should be kept if possible. For more instructions about the scene it is recommended to click on “Open help” button on the third tab of HUD inside the virtual world and by doing so open the manual to the scene.

2.8 Summary of results

The final model of tokamak Golem and its environment is an interactive virtual world where users can obtain information about the tokamak in a very convenient, understandable and easy way. Simulation of the real world tokamak Golem experience online provides users with an opportunity to explore this rare laboratory equipment at any time they want and from any place with internet access.

The model main features are:

- Understandable head up display posing as an interface to models interactivity
- Possibility of free exploring of the model
- Interactive naming system and parts descriptions
- Switches function to turn parts invisible or semi-transparent
- URLs of additional information about tokamaks components
- Understandable manual for the program
- Flexibility of expansion by other modelers

Virtual reality Golem has a great potential to help users understand the real tokamak better.

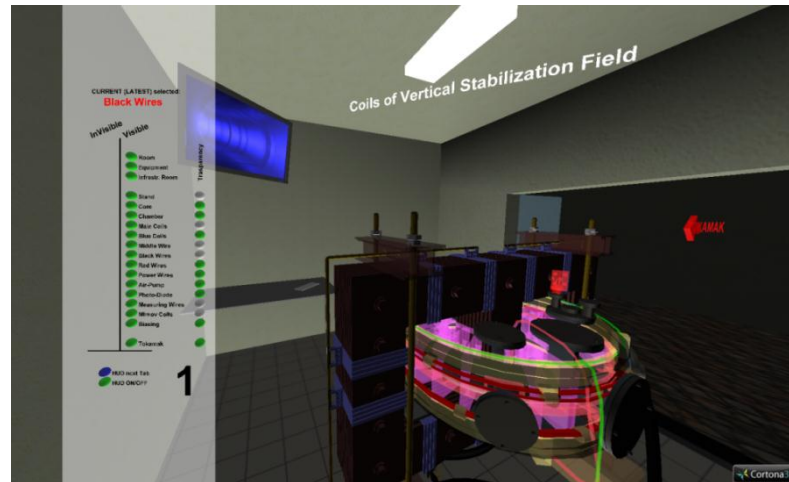


Figure 5 - The final version of tokamak Golem world

2.9 Organization of the report

Chapter 1 - Background provides basic information of what a tokamak is. The information presented there is fundamental for better understanding of the project.

Chapter 2 - Introduction introduces the project ideas, structure and purpose. It is an overview of whole project.

Chapter 3 - Creating 3D virtual model of tokamak Golem describes the steps in the working process taken to transfer the real device into its digital 3D representation.

Chapter 4 – Creating and optimizing the model in VRML describes VRML and shows how to edit and simplify the model of tokamak Golem in VRML

Chapter 5 - Interactivity and dynamics of the VRML model presents and explains interactive and dynamic features of the tokamak Golem virtual world.

Chapter 6 – Object adding manual is a detailed manual to adding components and extending the interactivity on the new parts. This chapter also shows how to exploit dummy objects in the scene.

Chapter 7 – Results presents the final results of the project with its technical details. Challenges stated in Introduction chapter are addressed in here.

Chapter 8 - Conclusion summarizes the positive aspects of the project and gives several suggestions for future improvements.

Chapter 3

Creating 3D virtual model of tokamak Golem

The problems encountered during the visualization process of the device are addressed here. All the steps necessary to create 3D digital model of an existing object (tokamak) are described in this chapter.

3.1 Taking pictures

Golem is enclosed in a small dark room. The space between Golem and walls of the room is barely more than 2 meters. Lighting provisions in the tokamak room are bad. There is no window to the room, just fluorescent lighting. Tokamak is a very complex device assembled from many parts. Cables and wires cover most of the body of the tokamak. In general Golem has a lot of small parts which are concealed by the other parts. Unfortunately some inner components of the tokamak could not be photographed.

To take useful photos of a device such as tokamak Golem under the given conditions was challenging. There must be pictures of Golem from all angles and sides to enable precise visualization. 10 to 15 photos were needed on each side of the device because one picture was not able to capture the whole view of the device. Some of the pictures required merging digitally while the rest could be used separately.

A good photography has clear image, not under or over exposed, has correctly set white balance and etc. Most of the pictures were taken with the aid of a tripod or flash because of the poor lighting. Tripod is a better option because flash usually leaves hard and sharp shadows which can hide needed details. However, tripod was not always possible due to the lack of space.

The problem with taking dimensions of Golem is resolved with the use of a cardboard square (Figure 6) with an edge exactly 10 cm long as a reference. After the tokamak part was shot together with the cardboard reference square, the dimensions of the part were then determined according to the reference square from the picture. The cardboard square had to be positioned in correspondence with the edges of the measured part. This approach works quite well for all objects with perpendicular edges, i.e. corners of 90°. On the other hand it is not a precise technique for determining the dimensions of rounded objects. The edges of the reference square and the edges of the measured object have to be in the same distance from the camera in the picture and round objects have no edges to refer to.



Figure 6 -Usage of the cardboard square

3.2 Adjusting pictures and taking dimensions

Out of the some 200 pictures taken on the spot, the sum was reduced to approximately half after screening. Bad pictures and unimportant ones were deleted. All neighboring good pictures were stitched together using Photomerge tool in Adobe Photoshop. These pictures provide the basic view of the tokamak which is very useful for 3D modeling. After stitching together as many photos as possible, the fundamental photo documentation of the tokamak was obtained. In addition a few videos were recorded as video can present more information about spatial environment than static pictures. Videos were used as a visual aid to how the device exactly looks like, so that connections between pictures from different angles can be easily sorted out. After merging the pictures, post-editing of some was needed to improve their quality. Adjustments of color, contrast and sharpness were made. Although pictures cannot catch much except a visual appearance of the device, they are fundamental for 3D modeling when there are no blueprints available to work with.

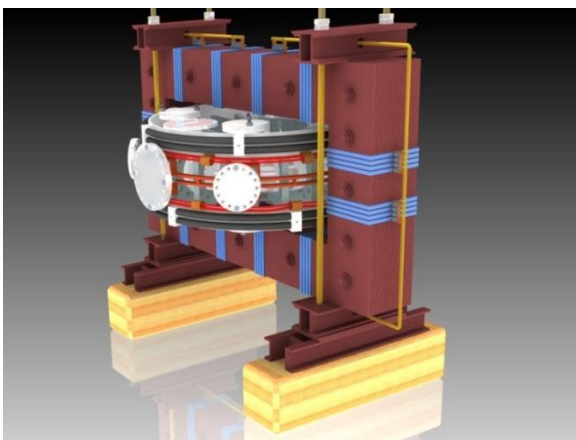
Taking dimensions from the picture is never 100% precise. Unfortunately, true measurement in tokamak room was not feasible. Many cables and other obstructions block the way. Some parts of the tokamak are partly or completely hidden and cannot be laid hand with measuring device upon. It is possible to measure dimensions with proper means but to precisely take all the dimensions of all the parts is beyond this project.

Deducting dimensions of the object from the reference square card box is as follow: Since the length of edges of reference square was known, it was easy to guess the length of the edges corresponding with the edges of the square by simple direct proportionality rule. (I.e. if the length of the reference square edge is 3 cm in the picture and length of the corresponding object edge is 9 cm then since 3 cm in the picture equal 10 in a real world than is obvious that 9 cm in the picture is 30 cm in reality)

3.3 Creating the 3D model of tokamak in Autodesk Inventor

Autodesk Inventor is professional software for creating 3D mechanical design of an object and its visualization. It helps unite data into a single digital model composition with its visual representation. With Autodesk Inventor, it is possible to create an accurate 3D digital prototype for the tokamak. The software is normally used for industrial prototyping. Inventor generates geometry automatically from the input dimensions. It is intuitive and powerful for creating precise 3D virtual models.

The first digital representation of tokamak Golem was created in Autodesk Inventor. When modeling in Inventor, it is possible to create separate 3D models of different parts of the tokamak and



assemble them later together. This provides useful simplification of an otherwise complex modeling procedure. Each part is saved separately in its own file. If only one file is accessed at the time the modeling process is less hardware demanding and more fluent and effective. The parts of Golem were created one by one. The creation starts with 2D sketch of each single part. The sketch is transferred into 3D via multiple tools. The most common techniques are extrusion and revolving from 2D. It means creating 3D object either by dragging the sketch along the path or revolving it around an axis. Very complex model can be made by simple combination of these two techniques. In addition, other more advanced ways to create the model were used.

Figure 7 - 3D model of Golem made in Inventor

After all the parts were made they had to be assembled into the tokamak. Instances of previously created tokamak components were inserted into one mutual file. Inventor allows comfortable assembling by using its relationships capabilities. Parts have geometrical and constructional relations between themselves. There are restrictions on movement of different parts according to their positioning to some other parts. (I.e. a vertically placed pole in a hole of horizontally positioned element can move just in vertical direction but it cannot be shifted outside of the hole horizontally Figure 8.) All the parts can be easily positioned by using relationships. Every part is linked to other related parts and its movement is restricted by them. When all the parts have their own movement restrictions assigned the model can be built just by simple shifting of parts to their correct position. 3D model of tokamak Golem was created at this point but the inner geometry and structure was not yet suitable for transferring to VRML.

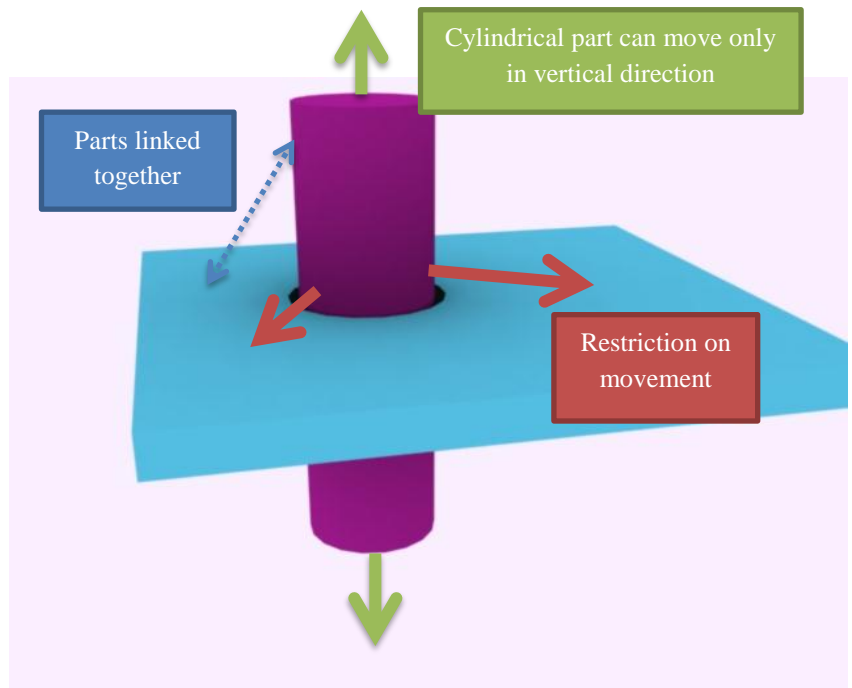


Figure 8 - Illustration of relationship between parts in Inventor

3.4 Using Autodesk 3Ds Max to redo the 3D model

Autodesk 3Ds Max, formerly 3D Studio Max is another application from Autodesk used in this project. Although it can appear to be similar to Inventor, 3D studio Max has completely different capabilities. Its purpose is to create, manipulate and animate 3D models. It is not an industrial design tool but rather software for making computer games, special effects of commercials and movies and in general for art-oriented 3D animated scenes. It also contains many plugins and tools for visualization. In 3Ds Max the modeler (user) has full control over his models from design and structural view. The modeling process in 3Ds max is unfortunately more difficult and slower than in Inventor. It is because of the larger number of options and settings. To design and model object with exact spatial characteristics and given dimensions is significantly time consuming.

Inventor models are transferable to 3Ds Max but they have degenerated inner structure beyond repairs. Therefore it was not possible to use previously made model of tokamak as the finished model. The Inventor Golem model could be however used as a reference for 3D model in 3Ds Max. It proved to be useful because 3D snapping tool could be used.

Working methodology and modeling techniques in 3Ds Max are different than in Inventor but they have similarities. Modeling process is more complex with more options in 3Ds Max and there is no effortless method to make a model. Having the reference model was a big help in making the new model. 3Ds Max can directly import files with geometry created in Inventor but the inner structure of the model was corrupted. Nevertheless the imported model still has the correct dimensions and the shape. By making this model partly transparent and locking it away in its own layer the reference object was made. Turning various parts of the reference model visible and invisible made part by part modeling process easier.

The easiest approach to modeling in 3Ds Max is cube modeling. Box is created and then shaped into the desired form. Structure of the model can be controlled. Modeler can directly affect every vertex, polygon, face or edge of the object. Overall control over the model is unlimited in 3Ds Max.

Model of tokamak Golem was created by cube modeling of tokamak components and grouping them together into the whole device. When creating the geometry 3D snapping tool was used on corners of the reference objects. Cube modeling was fast. All that was needed for some parts was to drag the corners of the modeled part and snap them to the adequate corners of the reference. For wires and similar uneven objects additional techniques were deployed. These include drawing the paths in 3D and dragging a profile along them, adjusting polygonal meshes by moving the vertices themselves or in some cases extrusion and revolving. Modeled objects were distributed into layers. Layers help to control grouped objects at once and make the work more organized (Figure 9). For smooth export to VRML it was necessary to keep the use of polygons to minimum and make as many parts from basic primitives as possible. Basic geometric primitives used are box, cone, cylinder and sphere. After creating a new model in 3Ds Max, the 3D model of tokamak Golem has a good structure to be exported to VRML

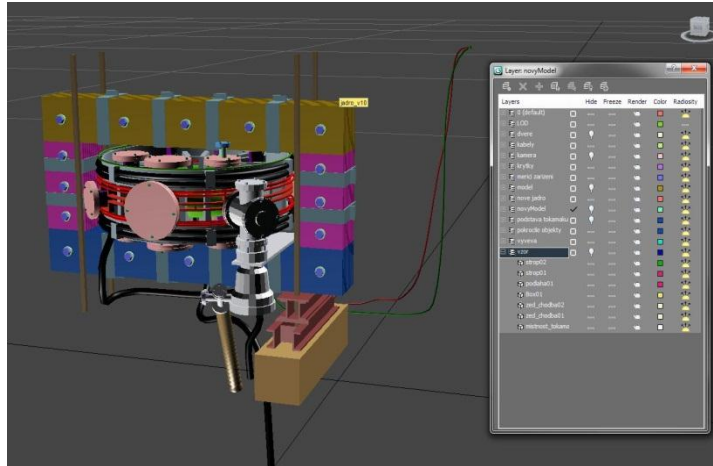


Figure 9 - 3D model of Golem distributed in different layers in 3Ds Max

Chapter 4

Creating and optimizing model in VRML 97

This chapter briefly describes Virtual Reality Modeling Language (VRML) and shows how to edit and simplify the model of tokamak Golem in VRML.

4.1 VRML

Virtual Reality Modeling Language is a programming language for defining virtual scenes. The language was designed to declare 3D digital environment referred in this project as virtual reality. There were many different languages to define 3D scenes in the past before VRML was created. Market was disunited and basically every company dealing with 3D graphics had their own modeling/programming language. VRML was a unifying instrument to multiple definitions of 3D scenes. VRML was created on the fundamental structure of the known graphic library OpenGL. The first version of VRML known as VRML 1.0 appeared in 1995. VRML 1.0 aimed to be used on the internet. VRML 97 was officially certified with ISO standard at the end of 1997 after over one year of editing and adjusting works on its first definition online. VRML 97 is sometimes referred to as VRML 2.0. VRML is still the most used language for defining 3D scenes online.

VRML is based on Open Inventor which provides higher level of programming on OpenGL. VRML uses hierarchy tree structure format where different branches can act separately and have different properties (material, transformation). On the other hand sub-branches can be affected at the same time when the structurally higher branch is edited. This feature is considered optimal by professionals for manipulating 3D scenes. VRML files are common text files. It is possible to write VRML code solely in a normal text editor. Universal UTF-8 coding is normally used for text coding. Every VRML code has to start with a head declaration containing VRML version and text encoding format. This header is recognizable sign that the text file is meant to be used as VRML file. The fundamental element of the tree structure in VRML is a node. A node is a piece of code that has a specific function. Every node has its name and inner content enclosed by curl brackets. VRML files use extension wrl or wgz when compressed.

VRML is old but it is still functional and widely used. VRML is platform independent. It aims to be used even with low bandwidth. Therefore the data from the internet are sent to a local client only once. After receiving the information about a 3D scene, data displaying is just a matter of the local client. It helps to deliver 3D interactive world with its interactivity in real time. VRML code is relatively simple to orient in and powerful to create interactive 3D world. However, VRML has also some drawbacks. It cannot simulate advance lighting effects. Objects in VRML have no shadows. VRML has mathematical representations only for basic primitives and for any other more advanced objects is IndexedFaceSet node created. IndexedFaceSet is literally a set of indexed faces which is usually very incomprehensive and it is almost impossible for programmers to make any adjustments of this node. Although the functionality of VRML can be improved by browsers loading external prototypes it is not a unified process and different browsers would support different functionality.

4.2 VrmIpad

VrmIpad 3.0 (Figure 10) is a VRML editor with many useful features. Writing VRML code in a common text editor is difficult and time consuming. VrmIpad makes the job much easier. The basic text editing functions remain but it is equipped with enhanced functionality aimed to VRML code editing. Functions such as smart dynamic error detection and syntax highlighting are a necessity. Smart autocomplete of half written name is time-saving. Node folding and thumbnailing make the file more organized and easy to read. It also shows a tree structure diagram and route diagram for every file. VrmIpad is a good medium for writing VRML code.

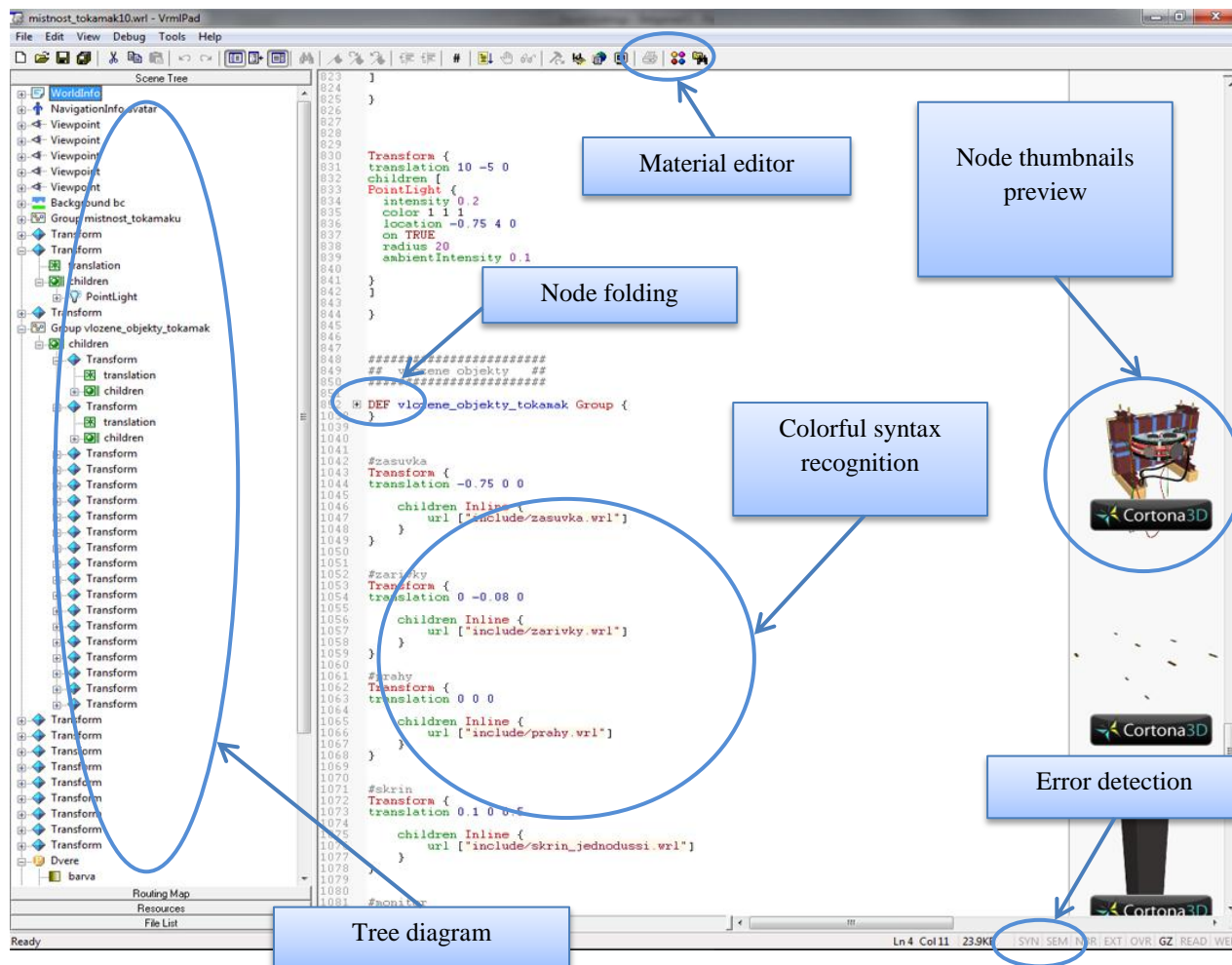


Figure 10 - VrmIpad and some of its features

4.3 Export from 3Ds Max to VRML97

File export from 3Ds Max to VRML 97 is a simple procedure (Figure 11). 3Ds Max has a built-in exporter into wrl format. 3Ds Max can convert basic geometric primitives into VRML basic geometry nodes but anything else would be automatically transformed into an indexed face set. Usage of this node is unavoidable for more advanced objects but in most cases geometry can be smartly subdivided into basic primitives' structures and exported as such. It guarantees the smallest file size and the simplest structure in VRML. It is best to make models only by using box, cone, sphere or cylinder so that the conversion to VRML can be kept simple and effective. An exported file from 3Ds Max to VRML is often loaded with unnecessary additional data. Original generic code created by 3Ds Max is imperfect and has to be revised and edited directly in VRML.

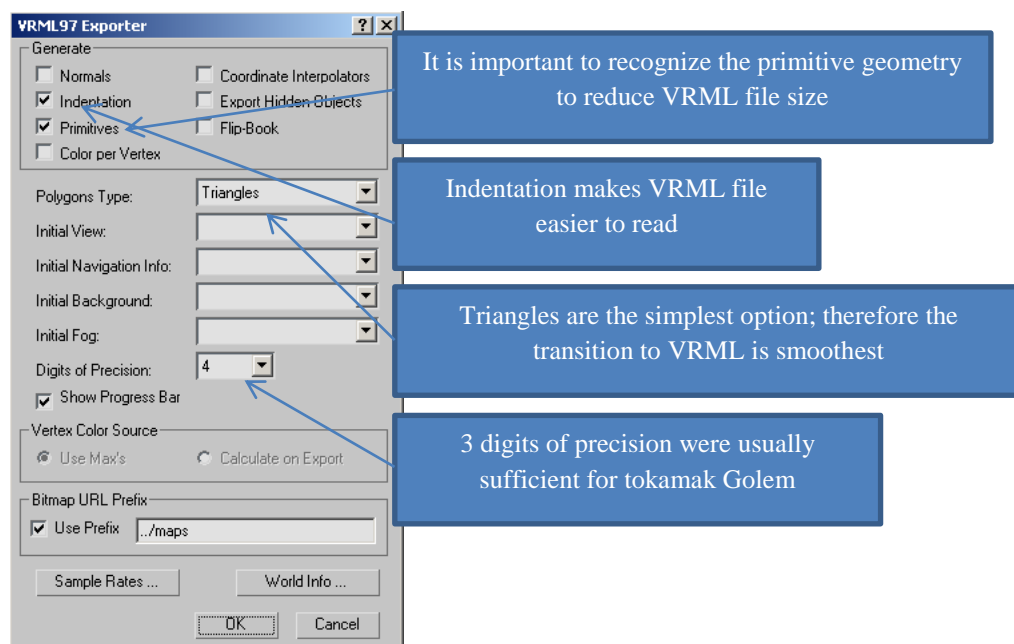


Figure 11 - Export dialog window in 3Ds Max to VRML97

4.4 DEF and USE in VRML

DEF and USE are two commands in VRML. DEF is for definition/naming of an object and USE is for using of the defined object. A good approximation of the relationship between DEF and USE structure in modeling is an object and its exact references. In VRML it means that any named node can be reused without writing the node again simply by calling its name (Figure 12). When a 3D model has many similar parts which differ in a few aspects but stay identical in some nodes, DEF and USE can be used very effectively. It can reduce the file size to minimum by reusing the nodes. Structure DEF and USE were used extensively for geometry of coils, stands, poles, wires, screws, caps etc. The usage of DEF and USE is not limited only on geometry. Materials, transformation, lights and others can be also reused by USE and DEF. The file size of the project VRML files was decreased many times by using DEF and USE because the model of tokamak Golem contains many repeated parts.

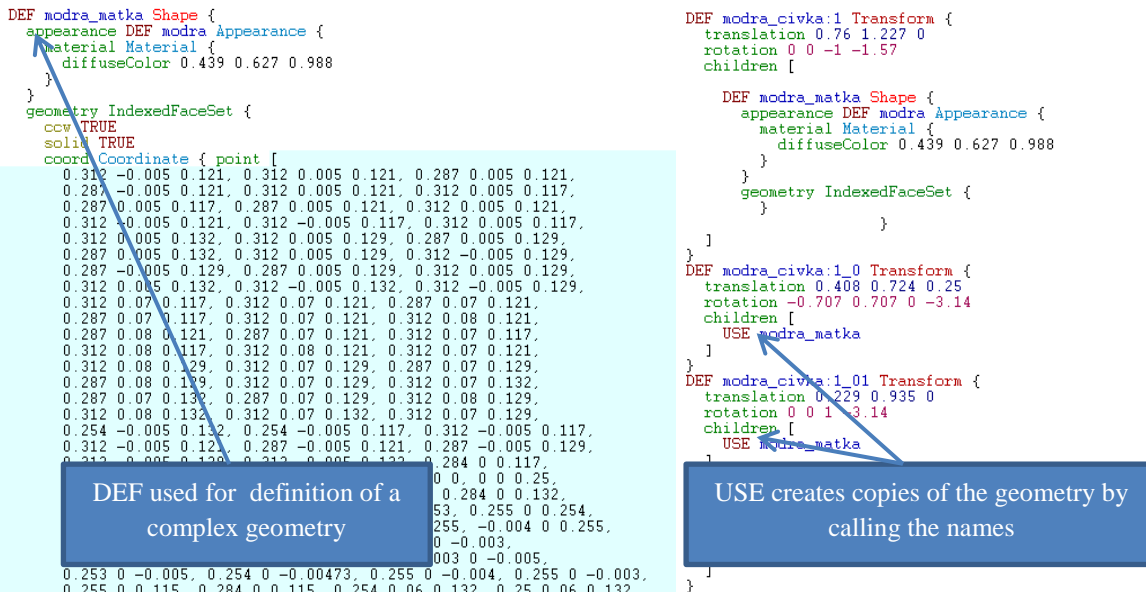


Figure 12 - DEF and USE in VRML

4.5 Optimization and LOD

After the model of tokamak Golem was completely transformed into VRML, it had to be optimized. Unnecessary data from imperfect export were deleted. DEF and USE were used to simplify the model and reduce the file size. Some numerical values were rounded according to demands on their precision. More than one third of all objects in the scene were not suitable for use in VRML and had to be remade in 3Ds Max and exported again (Figure 13). Different parts were separated into independent files and progressively loaded into the main virtual world using **include** nodes.

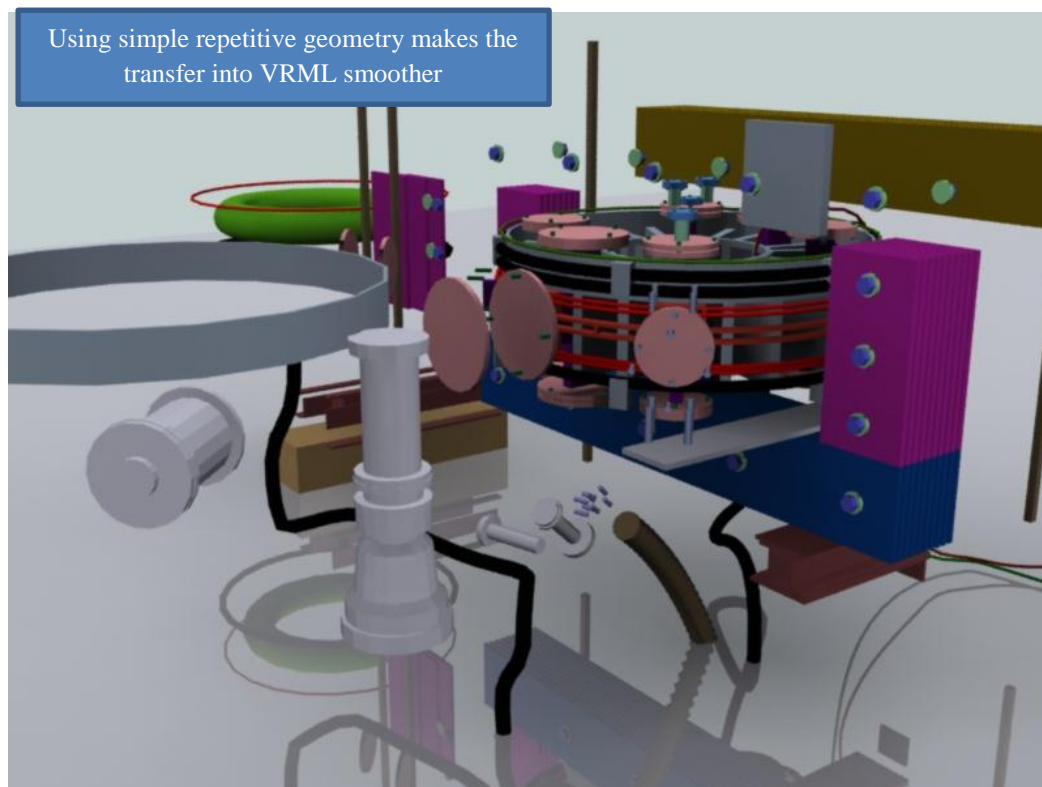


Figure 13 - Optimization in 3Ds Max. Many parts were remade using just simple geometry

LOD means level of details and by itself it is one of the many VRML's nodes. It is used to simplify geometry of a virtual scene. Using LOD is a common practice in all 3D related applications. It is widely used in video games and VRML worlds. LOD determines the quality of displayed model according to the viewer-model distance. When avatar (the virtual representation of a viewer inside the immersive world) is close to 3D geometry of the model the model appears detailed but when he goes further from the object the complex geometry is swapped to simple and less precise one. It can also unload the model from the virtual world completely if the avatar is too far to see it. More complex virtual worlds would not be playable without LOD because of the abundant data displayed at once.

Chapter 5

Interactivity and dynamics of the VRML model

Dynamics and interactivity are important elements of the scene. Interactive and dynamic features of tokamak Golem virtual world are described in this chapter.

5.1 Introduction to interactive world of tokamak Golem

After transferring the complete model from 3Ds Max into VRLM and adjusting VRML data, the virtual scene is static and lifeless. All the objects are stationary and inactive. Dynamics and interactivity can improve the scene. They will make it more appealing to users and more usable as an educational tool. Dynamics refers to movements of objects in the scene. Interactivity makes the original static scene respond to actions of users. Every user in VRML is represented by avatar. Since avatar is a digital representation of the user, all input data are the data received from avatars actions. They can be either obtained from avatars location, orientation, his position relevant to a particular object in the scene or avatars direct interaction. Avatar can directly interact by touching objects (mouse click, mouse over, etc.). Interactive objects can recognize interactions with avatar and act according their programmed behavior. Head up display (HUD) was added into the scene to widen the options of interaction and to make the virtual scene easily controllable. Interactivity brings the opportunity to change aspects of the scene to users' likings or needs. An interactive world is a high value educational asset because an interactive virtual world bears much more information than a static one.

5.2 Interactive and dynamic objects in the scene

Interactive and dynamic objects controlled via buttons from HUD

- Tokamak Golem components – visibility and semi-transparency on and off
- Lights – intensity high and low
- Animation –animation on and off
- HUD – HUD display on and off
- Viewpoints – viewpoints from 1 to 8
- Description text above the tokamak – turn on and off
- Help file – manual open
- Red arrows- on and off

Interactive and dynamic objects controlled directly

- Tokamak Golem components – part moves, interactive name of the part is shown on HUD and interactive description of the part appears above the tokamak when mouse cursor is over the component, open description file when mouse clicked at the component
- Buttons – change color and/or position when clicked on them by mouse, change transparency when mouse cursor is over them
- HUD – moves when dragged by mouse
- Doors – can be closed and opened

- Monitor in the tokamak room – changes the screen animation when clicked at
- White text about the tokamak – shows the description of the part the user is pointing at
- Sliders – sliders on small resistors in the infrastructure room are movable

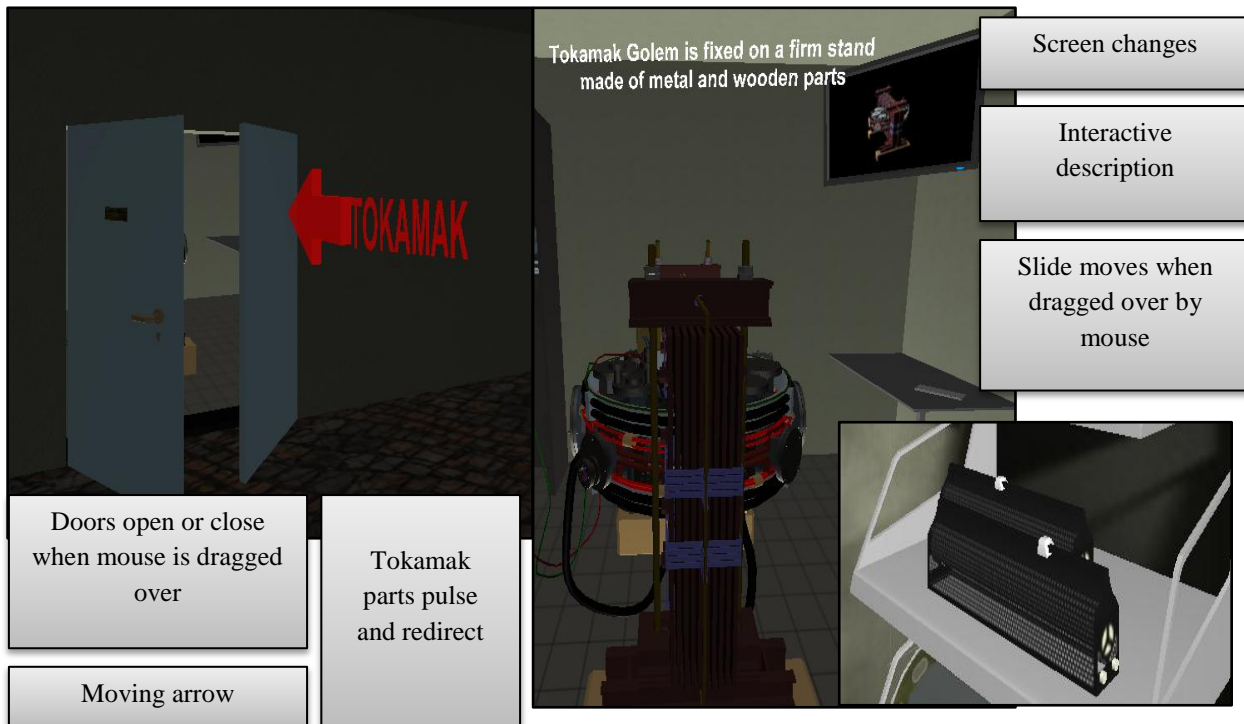


Figure 14 - Common interactive / dynamic objects

5.3 Head up display control panel

HUD is a virtual interface which is presented in front of avatars eyes. Many elements of virtual world of tokamak Golem can be controlled via buttons from there. It is movable and its location can be adjusted to suit the comfort of the user. Sometimes it is useful to hide HUD completely for better orientation in the scene by pressing the button **HUD ON/OFF**. Buttons on HUD are mostly of on/off function. HUD consists of 3 tabs which are sequentially cycled by button **HUD next Tab**. The first tab contains buttons for interacting with the tokamak model. The second tab has pre-designed buttons for extension works on the model and for addition of new parts. The last tab contains viewpoints selection, animations and additional settings (Figure 15).

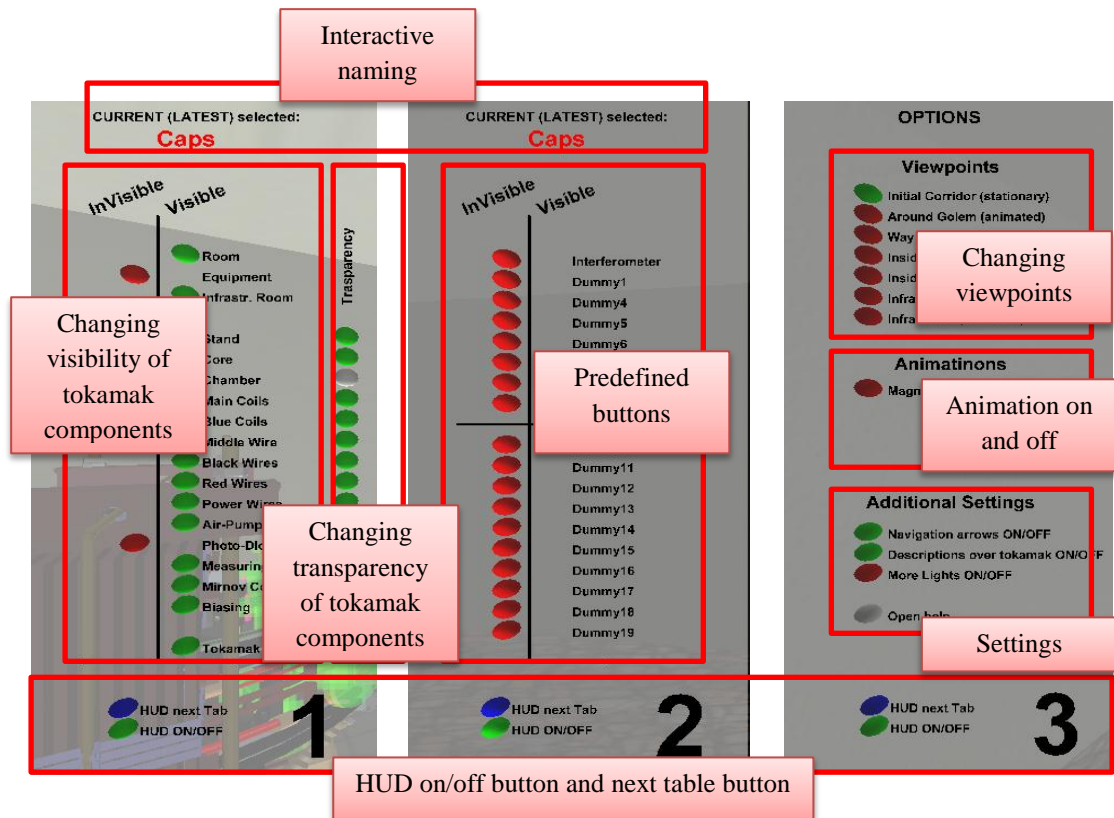


Figure 15 - HUD three tabs

5.4 File system of the model (Figure 16)

The virtual world of tokamak Golem consists of one main file **tokamakGolem.wrl** and many additional files. The main file contains code for interactivity, views, geometry of the corridor and tokamak room, HUD panel and general information about the virtual scene. Textures load from **bitmaps** folder. The main file loads the object files in **include** folder. In folder **include unzipped** are uncompressed wrl files which are not used. They are presented only for extension works on the project if needed. Folder **doc** contains **helpTokamak.pdf** file which is the manual for tokamak Golem virtual world and **mc.pdf** which is the description file for Mirnov Coils. The **tokamak_final_petr** folder contains all the files needed for infrastructure room [10].

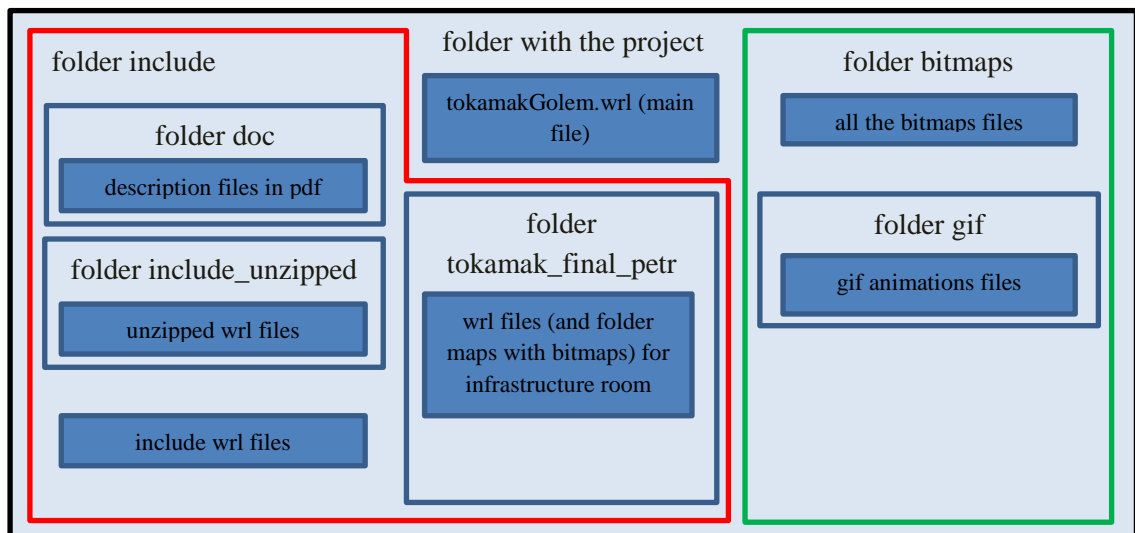


Figure 16 - File system of the model

5.5 Structure of the scene

Inner code structure of tokamak Golem virtual world is simple and efficient. The main file contains the basic information about the virtual world and it loads the information about tokamak and other objects. The scene objects are mostly in separate files but they are all loaded into the main file. In the main file the whole device is assembled piece by piece and the final scene is created. In addition the infrastructure room is also included and connected to the virtual world. The main file is divided into logical segments. The following simplified scheme (Figure 17) shows the most important parts of the file. Dark red objects are prototypes and bright red are their instances.

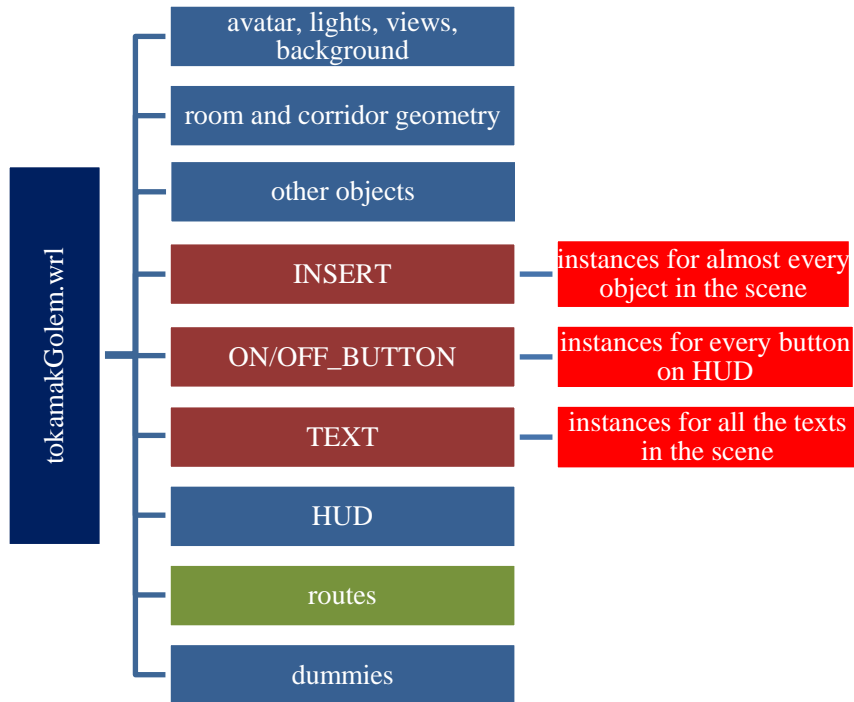


Figure 17 - Structure of the main file

The code of the project files was optimized for easy expansion of interactivity on new parts of the model. Most of the code creating interactivity is in the PROTO code structure. PROTO in VRML is used to create prototype which can contain unlimited amount of nodes and have instances. This approach reduces the total amount of code necessary for creating the desired effect. Otherwise repetitive nodes can be placed in prototype only once and used in many instances. It also helps to transfer the same interactive behavior to new objects. Instances of the same prototype inheriting all the same behavior can have different initial variables. Using PROTO in VRML is similar to object oriented programming. PROTO can be imagined as an interface to its instances. Some properties of instances can be accessed from outside of PROTO. One of the most fundamental structures creating interactivity in the tokamak scene is prototype INSERT. Instances of prototype INSERT are used to load and include individual objects into the scene. Every part of the tokamak has its own wrl file where the object is saved. To build the tokamak all the parts have to be loaded into one file. An instance is created for every included file. Included objects obtain automatically the code (behavior) of the prototype. Another necessary prototype is ON/OFF_BUTTON. Its instances are used as buttons. Buttons are located only on HUD and used as controlling means to the scene interactivity. They are routed to other objects in the scene. They can send the information about their state or change of state to objects in the scene and doing so initiate the programmed behavior of the objects. On the picture (Figure 18) is shown a simplified version of communication process in the scene.

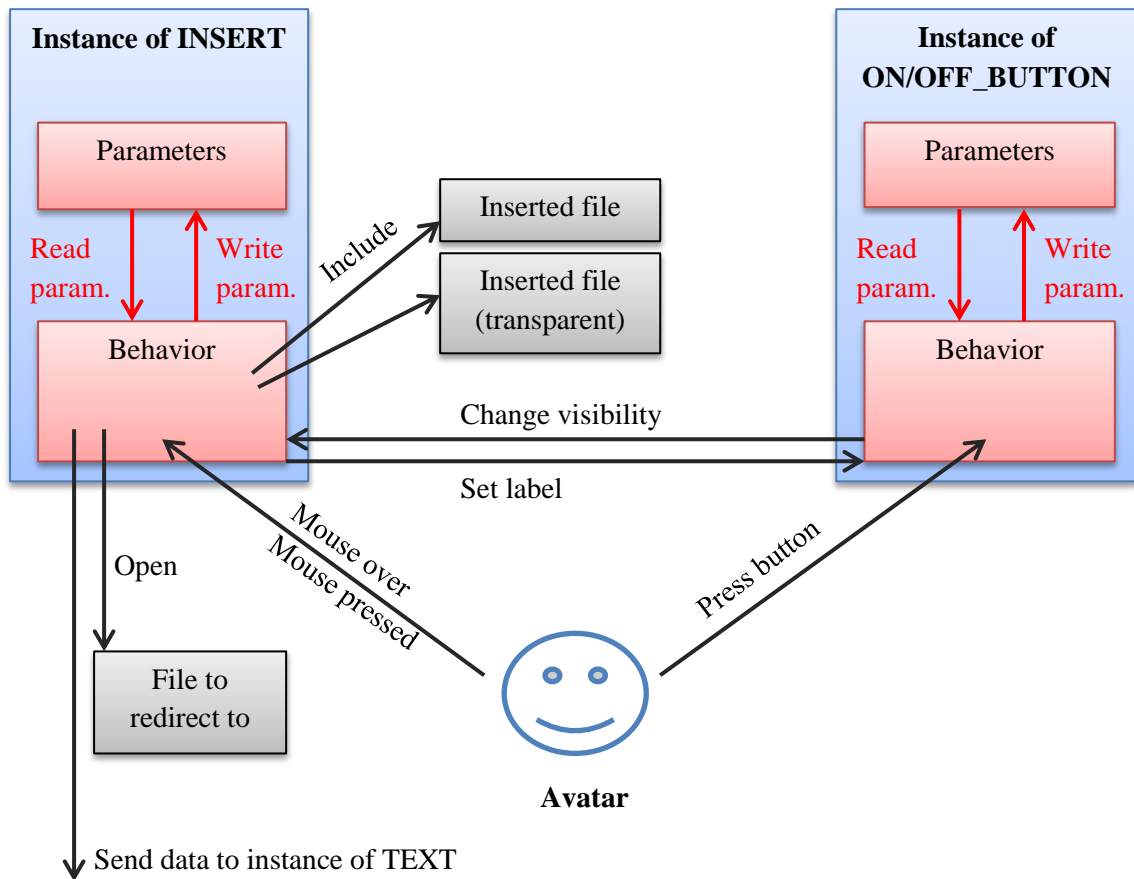


Figure 18 - Object communication

The interactivity in the scene is fairly complex and for better understanding of the whole program it is necessary to view the main file and read the code commentary. It is also useful to see routes map included on the CD. It is not shown in the report because the picture is too complex to be printed on multiple pages.

Chapter 6

Object adding manual

The chapter goes thru all the stages of adding new part into the scene. It shows what changes have to be done in the code to add the existing interactivity to the new part. It also explains how to use dummy objects in the scene.

A basic knowledge of VRLM is required to understand the following manual. Objects which are to be inserted into the scene should be already modeled and transferred into VRML. New objects can be made the same way which is described in previous chapters of this project (modeled in 3Ds Max, transferred into VRML and optimized).

6.1 Suitable objects

Any individual VRML scene can be inserted as an “object” into the tokamak virtual world. It is recommended to insert only geometrical objects without any interactive behavior. The main tokamak scene was created to be easily extended by relatively simple geometry VRML files. The objects can be either moving (animation) or stationary. An example of suitable files for insertion is any file from **include** folder except **door.wrl** as it is an external prototype. Although the object (VRML file) for insertion is to be created before reading this manual, there are some practical tips for modeling suitable objects.

- Suitable 3D modeling software is 3Ds Max. Modeler has good control over the model structure and it can export to VRML. Reference files on included CD are native 3Ds Max files and therefore can be opened in the software.
- There are several files in **reference3D** folder in the project. Each one of them contains the same main scene of tokamak Golem. The scene geometry is a copy of the VRML scene. There are more files (file types) because different software can open different file types. It is a good practice to open one of the files in 3D modeling software before modeling new object for Golem and use it as a reference. If the object is created by this way, it will fit the VRML model of tokamak Golem perfectly and no adjustments will have to be done later.
- Use as little polygons as possible for smaller file size.
- Build the model mostly out of basic primitives.
- Edit the model in VRML after it is exported. Use DEF, USE and LOD structures in VRML.
- Test the model in VRML viewer

6.2 Adding new objects using dummies

Process of adding an object into the scene can start when a VRML file containing the object is created. If the transparency function is to work, the copy of the same file has to be created and named **filename_transp.wrl**. The material of the object in **filename_transp.wrl** has to be edited and changed to semi-transparent. Both files should be uploaded into **include** folder. Another file with description of the part needs to be uploaded into **include/doc/** as **filename.pdf** if the redirection function is wanted. Now the main file of tokamak Golem virtual scene **tokamakGolem.wrl** must be edited.

There are 15 INSERT instances already prepared and connected with buttons. The only thing that needs to be done to add an object is to edit the properties of the instance (Figure 19). All 15 instances are located at the end of the main file and connected to the buttons (from dummy4 to dummy19) on the second tab of HUD.

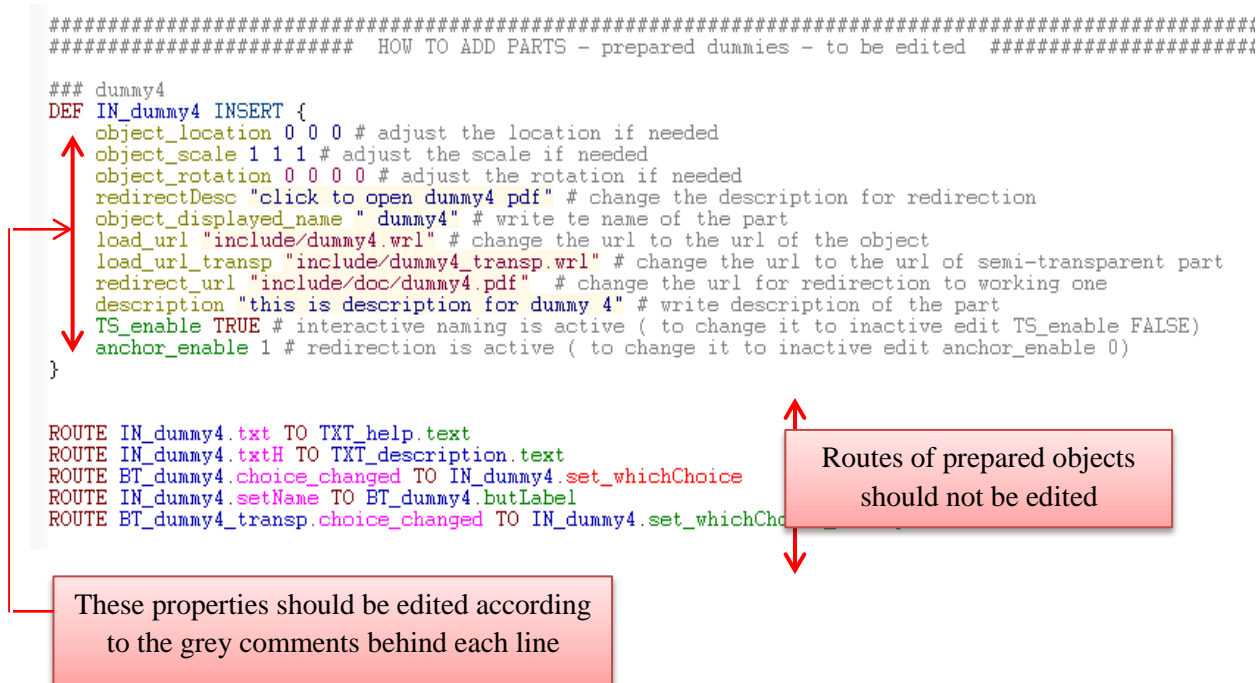


Figure 19 - Prepared dummy instance

The object has been added and has the functionality of other parts of tokamak Golem. The initial states of buttons changing visibility and transparency can be changed if it is desired. The buttons must be found in the file. Their location is inside the HUD transform node (lines 2210 to 2264). Edited code should belong only to the buttons containing the same name as has the INSERT instance. For **IN_dummy4** are adequate buttons **BT_dummy4** and **BT_dummy4_transp** (Figure 20). Button property “state” can be either TRUE (button is turned on when the scene is loaded) or FALSE (button is turned off when the scene is loaded).

```
DEF BT_dummy4 ONOFF_BUTTON {butLabel " Dummy4" state FALSE shiftHUD -0.1 locHUD -2 -23.4 }
DEF BT_dummy4_transp ONOFF_BUTTON {butLabel "" state TRUE shiftHUD -0.1 locHUD -1.3 -23.4 chngPos 0 0 0 offColor 1 1 1 }
```

Figure 20 - Two buttons related to the IN_dummy4

6.3 An illustrative example how to add an object (whole procedure)

- Files **dummy.wrl** and **dummy_transp.wrl** were saved in the include folder (Figure 21). The files are almost the same. The only difference is that **dummy_transp.wrl** has transparency set to 50% (Figure 22).
- Main file of the project **tokamakGolem.wrl** was opened

File Name	Date	Type	Size
dummy.wrl	17.4.2011 13:33	WRL File	1 KB
dummy_transp.wrl	17.4.2011 13:33	WRL File	1 KB
end.wrl	17.4.2011 13:33	WRL File	1 KB
femaleScrews.wrl	15.4.2011 14:26	WRL File	7 KB
		WRL File	2 KB
		WRL File	32 KB

Figure 21 - Include folder

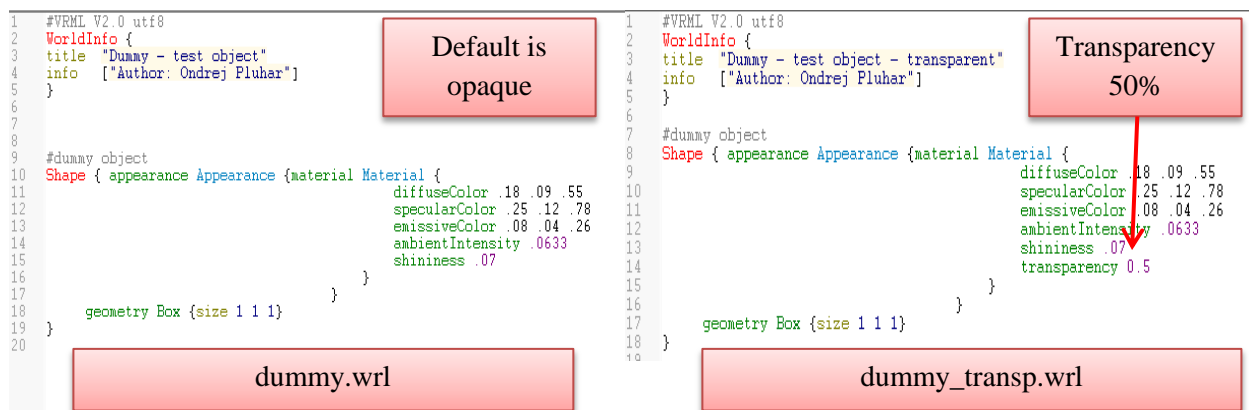


Figure 22 - Dummy files

- Two instances of **ONOFF_BUTTON** prototype were created in the file (Figure 23). The location is line 2210 and 2211. It is important for the instances to be created somewhere in the space labeled **SECOND TAB** because they have to be inside the **HUD** code structure.

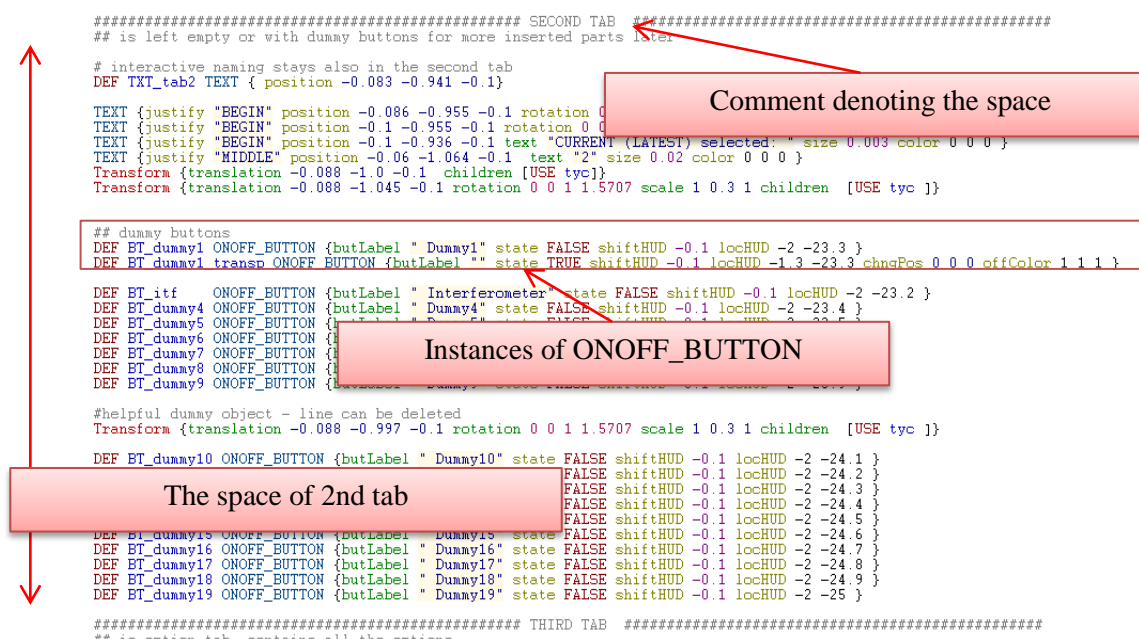


Figure 23 - Buttons

- Properties of two buttons are shown on the picture below (Figure 24)

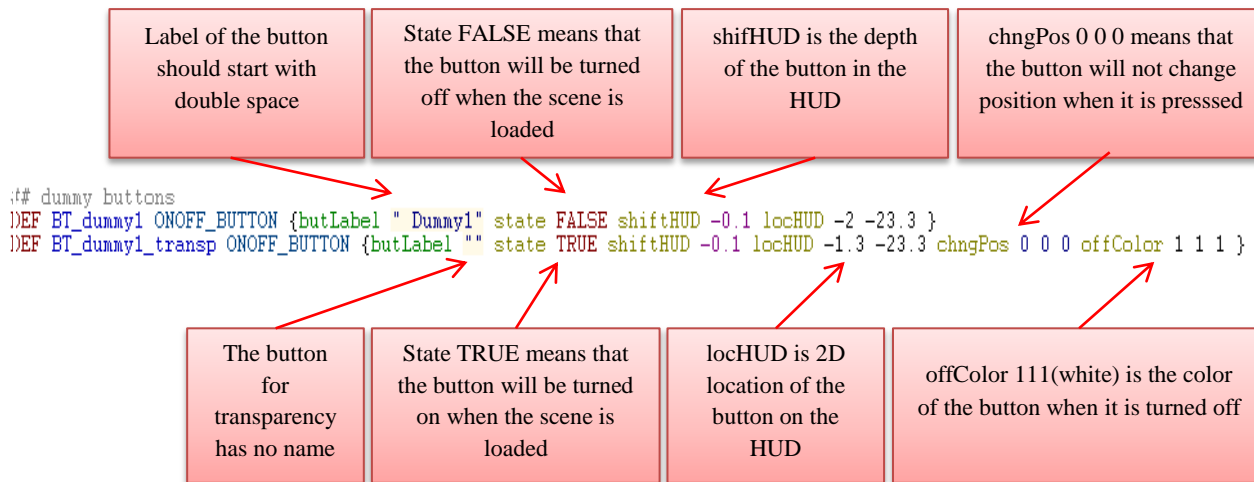


Figure 24 - Button properties

- Instance of INSERT prototype was created at the end of the file. Comments explain the purpose of the properties (Figure 25)

```

DEF IN_dummy1 INSERT {
  object_location 0.13 1 0.12 # dummy object location (default is -0.75 0 0)
  object_scale 2 2 1 # dummy object scale, default is 1 1 1
  object_rotation 0 0 0 # dummy object rotation, default is 0 0 0
  # default for all the strings is empty string ""
  redirectDesc "click to open dummy pdf" #this text will appear next to
                                         #the mouse cursor when it is pointed at the object
  object_displayed_name " dummy dummy" # the name displayed in interactive naming (red text in HUD).
                                         # this text can be also routed to button label
  load_url "include/dummy.wrl" # the url of the source file (wrl file) containing the object
  load_url_transp "include/dummy_transp.wrl" # the url of the source file for semi-transparent version (wrl file)
  redirect_url "include/doc/dummy.pdf" # file dummy.pdf at this location will open when clicked at the part
  description "this is a box object with description" #description text that appears above the tokamak
  TS_enable TRUE # is the naming active (true active, false inactive) - default is active
  anchor_enable 1 # is the puls movement and redirection active (1 active, 0 inactive) - default is inactive
}

```

Figure 25 - Instance of prototype INSERT

- In the last step were added routes (Figure 26)

```

# the inserted object sends content of the object_displayed_name to the red text on HUD
ROUTE IN_dummy1.txt TO TXT_help.text

# the inserted object sends content of the description to text above the tokamak
ROUTE IN_dummy1.txtH TO TXT_description.text

# button sends its state to inserted object (visibility on and off)
ROUTE BT_dummy1.choice_changed TO IN_dummy1.set_whichChoice

# not compulsory but useful - unifies the names of insert and button label
#(the name from insert overwrite the label of the button)
# the inserted object sends content of the object_displayed_name to button label
ROUTE IN_dummy1.setName TO BT_dummy1.butLabel

# button sends its state to inserted object (transparency on and off)
ROUTE BT_dummy1_transp.choice_changed TO IN_dummy1.set_whichChoice_transp

```

Figure 26 - Routes

- The dummy object is now inserted and fully functional (if the redirection is to work, the file **dummy.pdf** has to be saved in the location of **include/doc/dummy.pdf**)

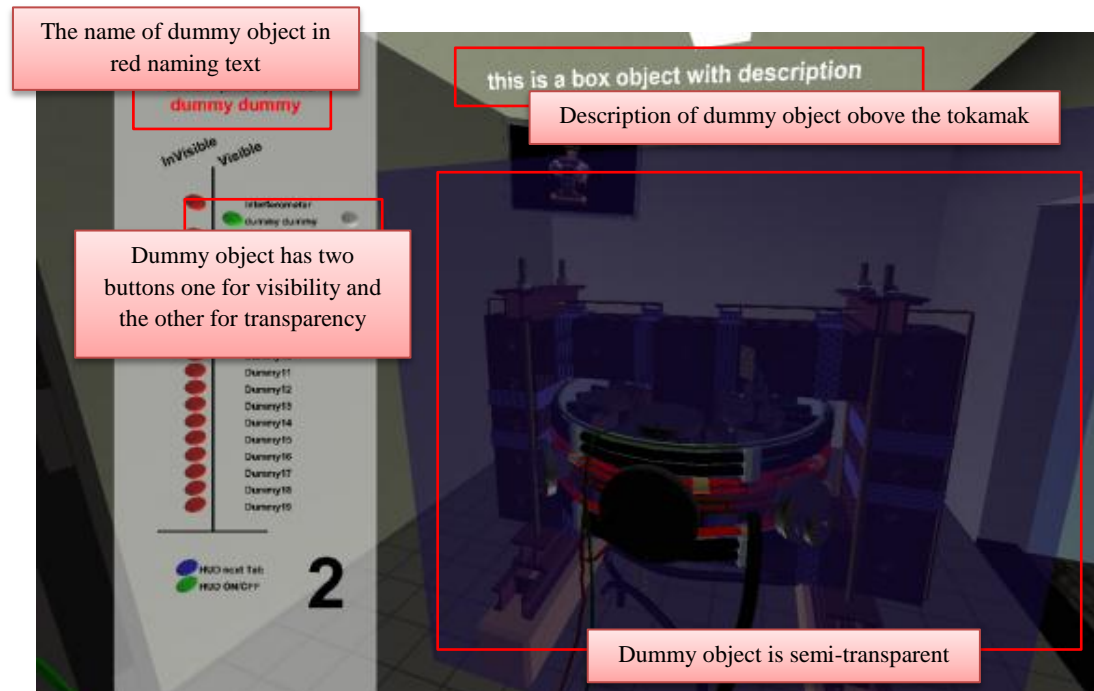


Figure 27 - Inserted dummy

The following picture (Figure 28) shows all the changes made to the main file to add a new part.

```
## dummy buttons
DEF BT_dummy1 ONOFF_BUTTON {butLabel " Dummy1" state FALSE shiftHUD -0.1 locHUD -2 -23.3 }
DEF BT_dummy1_transp ONOFF_BUTTON {butLabel " " state TRUE shiftHUD -0.1 locHUD -1.3 -23.3 chngPos 0 0 0 offColor 1 1 1 }

+

DEF IN_dummy1 INSERT {
  object_location 0.13 1 0.12 # dummy object location (default is -0.75 0 0)
  object_scale 2 2 1 # dummy object scale, default is 1 1 1
  object_rotation 0 0 0 # dummy object rotation, default is 0 0 0
  # default for all the strings is empty string ""
  redirectDesc "click to open dummy pdf" #this text will appear next to
  # the mouse cursor when it is pointed at the object
  object_displayed_name " dummy dummy" # the name displayed in interactive naming (red text in HUD),
  # this text can be also routed to button label
  load_url "include/dummy.wrl" # the url of the source file (wrl file) containing the object
  load_url_transp "include/dummy_transp.wrl" # the url of the source file for semi-transparent version (wrl file)
  redirect_url "include/doc/dummy.pdf" # file dummy.pdf at this location will open when clicked at the part
  description "this is a box object with description" #description text that appears above the tokamak
  TS_enable TRUE # is the naming active (true active, false inactive) - default is active
  anchor_enable 1 # is the puls movement and redirection active (1 active, 0 inactive) - default is inactive
}

# the inserted object sends content of the object_displayed_name to the red text on HUD
ROUTE IN_dummy1.txt TO TXT_help.text

# the inserted object sends content of the description to text above the tokamak
ROUTE IN_dummy1.txtH TO TXT_description.text

# button sends its state to inserted object (visibility on and off)
ROUTE BT_dummy1.choice_changed TO IN_dummy1.set_whichChoice

# not compulsory but useful - unifies the names of insert and button label
#(the name from insert overwrite the label of the button)
# the inserted object sends content of the object_displayed_name to button label
ROUTE IN_dummy1.setName TO BT_dummy1.butLabel

# button sends its state to inserted object (transparency on and off)
ROUTE BT_dummy1_transp.choice_changed TO IN_dummy1.set_whichChoice_transp
```

Figure 28 - Summarization of all changes in the code of the main file

6.4 Editing existing components

To change the interactivity of an existing component it is necessary to find and edit the parameters of the corresponding INSERT instance. The easiest way to find the correct instance in the main file is to use find function of the text/VRML editor. Almost every text editor can search thru the file for a given expression. For obtaining the component name the scene should be opened in VRML viewer. The name of the component of tokamak appears in red text on HUD when mouse cursor is pointed at it. When the name is known the main file **tokamakGolem.wrl** can be searched for the name. Parameter **object_displayed_name** of INSERT instance would be found (Figure 29). Therefore the instance is found as well. Other parameters can be changed the same as when a new part is added. To change more than the basic interactivity it is recommended to read the comments of the main file and understand the structure. This describes only fundamental editing of the main file.

```
DEF IN_dummy1 INSERT {
  object_location 0 13 1 0.12 # dummy object location (default is -0.75 0 0)
  object_scale 2 2 1 # dummy object scale, default is 1 1 1
  object_rotation 0 0 0 # dummy object rotation, default is 0 0 0
  # default for all the strings is empty
  redirectDesc "click to open dummy pdf"
  object_displayed_name " dummy dummy" # the name displayed in interactive naming (red text in HUD),
  # this text can be also routed to button label
  load_url "include/dummy.wrl" # the url of the source file (wrl file) containing the object
  load_url_transp "include/dummy_transp.wrl" # the url of the source file for semi-transparent version (wrl file)
  redirect_url "include/doc/dummy.pdf" # file dummy.pdf at this location will open when clicked at the part
  description "this is a box object with description" #description text that appears above the tokamak
  TS_enable TRUE # is the naming active (true active, false inactive) - default is active
  anchor_enable 1 # is the puls movement and redirection active (1 active. 0 inactive) - default is inactive
}
```

This expression was searched for

Figure 29 - Finding an instance

Chapter 7

Results

Description of the final product is revealed in this chapter. The challenges stated at the beginning are addressed and solutions to them are explained. Furthermore important data about the final product is also presented in this chapter.

7.1 Final Model

The final VRML model of tokamak Golem and its environment consist of tokamak Golem, the equipped room where the tokamak is located, the corridor next to the room and the infrastructure room. There are also several common objects (doors, lamps, electric plugs) in the scene. The resulted virtual world of Golem is not an exact copy of the real scene but it catches all the important features of the tokamak and depicts it in complete and understandable way. The model cannot be mistaken for any other tokamak and the rooms are clearly the same rooms as are at the Faculty of Nuclear Sciences and Physical Engineering in Prague 1. The functionality of the model has educational character. The model does not behave as the real tokamak does in the contrary there are features that the real tokamak can never have. The main features are: different parts of the tokamak can be turned invisible or transparent, names and descriptions will appear when pointed at various parts of tokamak and some objects can trigger the opening of additional files. Purpose of the model is purely educational.

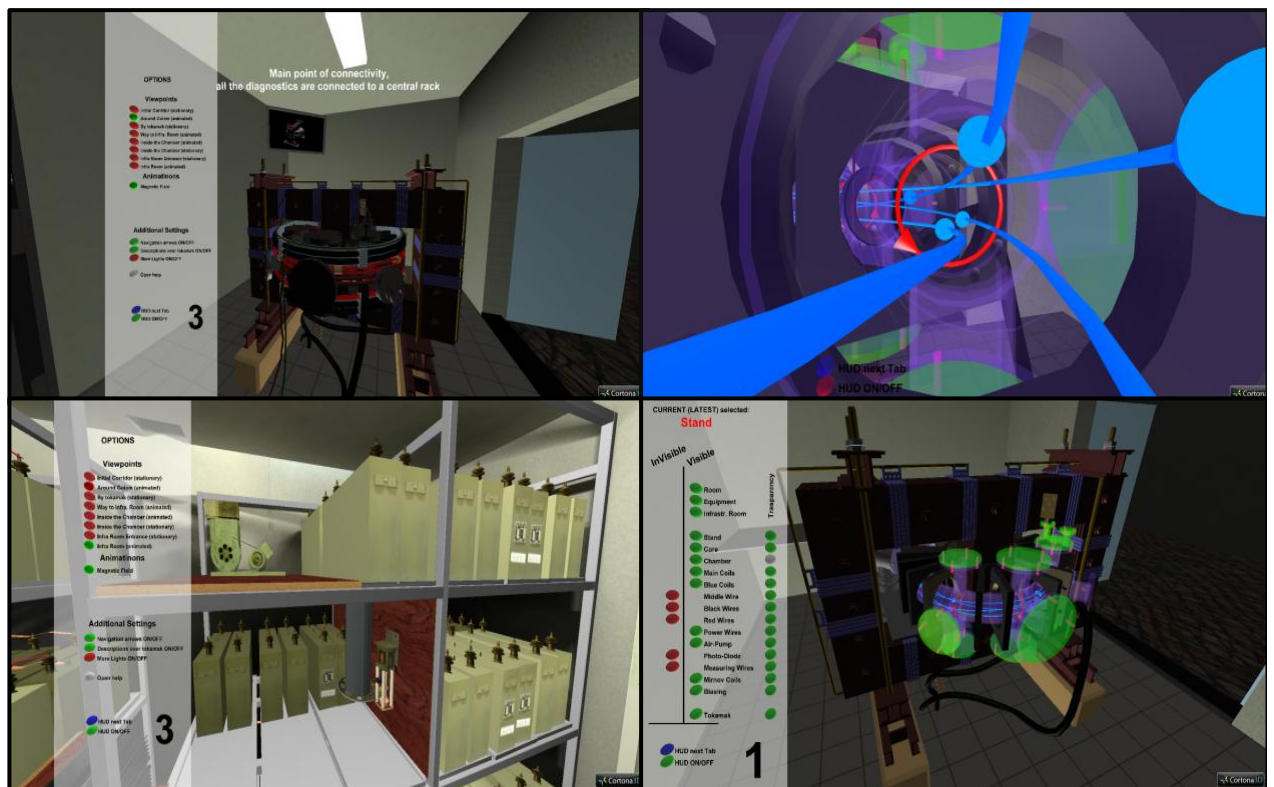


Figure 30 - 4 different views in the virtual scene

7.2 Addressing the challenges

Availability of data necessary for reconstruction; Many photos from various angles were taken and adjusted to serve as initial data for reconstruction. Some dimensions were guessed based on the reference object from the picture. Although the proportions of the model are visually correct the model is not a precise copy. Suitable data for reconstruction of Golem were taken but proper measurements of all the parts would be needed to exactly recreate the tokamak.

Modeling of Golem; Modeling of tokamak Golem was a complicated process with multiple stages. The most precise model was created in Autodesk Inventor. The model suitable for export to VRML was made in 3Ds Max. Almost half of the objects had to be remodeled again after exporting to VRML. Complex geometry objects were subtracted by composed objects made of basic primitives. Parts of tokamak were modeled piece by piece according to the data acquired from the pictures and measurements. By assembling all the parts together whole device was created. The model of tokamak Golem which was adjusted for export to VRML was created.

Data optimization; DEF and USE were used for repetitive objects in the scene to enable smaller file size and code. LOD was used to hide unnecessary geometry and to shorten the loading time of included files. Unnecessarily precise numbers with too many decimals were rounded. Wrongly exported geometry was reedited in VRML.

Internal structure; The main file is well commented and organized. Its code is logically divided into different sections. Each section contains objects with the same character or functionality. Internal structure of the VRML world is suitable for adding new parts. Separate parts of tokamak Golem are kept in separate files. Objects can be inserted into the main file as an instance parameter where the prototype has the functionality. The parts included by this way will have the functionality of the prototype. This simplifies the adding process on minimum. Dummy objects are also used to facilitate the process of adding new parts. Instances of new parts are already created as dummy instances and what is needed to include a new part is just to change parameters of an instance.

Educational tool; Interactivity of the model is especially suitable for education. HUD can be easily remembered because it is simple and user friendly. The model is prepared to be extended by professors or students and therefore suit individual needs. The model can show hidden parts of the device and also provides users with all the information necessary. The information revealed is interactively selected according the users actions inside the scene. Educational materials need to be easily accessible. The tokamak Golem VRML world will be placed online to be always available for students.

7.3 Frame rate test of the final scene

Laptop Lenovo Ideal Pad Y560 was used for testing to play the Golem scene. It has the following parameters:

- CPU - Intel (R) Core(TM) i7 CPU Q 740 4 Cores @ 1.73GHz
- RAM - 4GB
- Graphic adapter - ATI Mobility Radeon HD 5730 (RAM 1GB)
- External display resolution 1920×1080 and frame rate 60 frames per second

The results are the same for VRML viewers BS Contact and Cortona 3D

Action	Frames per second
Loading of virtual scene	20-40
Moving inside the tokamak room	40-60
Moving inside the infrastructure room	30 -55
Changing of view	30-40
Pointing at active parts of tokamak	30-50
View inside the chamber	50 - 60
All semi-transparency turned on	40-50

Table 2 - Frames rate

An average frame rate does not drop below 30 fps even when all the interactive functions are being used. The world is perfectly playable on this hardware.

7.4 Time spent on the project

The table (Table 3 - Time) shows how much time was dedicated to different steps in doing this project. Stated times are rounded to hours.

Action	Time (hours)
Taking pictures	4
Consultations and writing emails	6
Inventor modeling	20
3Ds Max modeling first stage	30
VRML LOD adjustments	30
3Ds Max clearing model and remodeling	20
VRML interactivity	50
VRML refinement	10
VRML touch ups and correcting	20
Report writing and other documentation	70
Additional project related work	20
Total	280

Table 3 - Time

7.5 Files details

File name	Name of the original file without extension
Size (KB)	Size of the original file
Size zip (KB)	Size of the compressed version
Faces count	Total count of faces in the file (basic primitives are not counted)
File type	Extension of the original file
Description	Description explaining the purpose of the file

Table 4 - File details legend

#	File name	Size (KB)	Size zip (KB)	Faces count	File type	Description
1	airPump	107	22	2944	wrl	tokamak part
2	airPump_transp	107	22	2944	wrl	semi-transparent version
3	animationMF2	463	66	1472	wrl	inserted VRML animation
4	biasing	12	3	304	wrl	tokamak part
5	biasing_transp	12	3	304	wrl	semi-transparent version
6	blackWire	67	14	1896	wrl	tokamak part
7	blackWire_transp	67	14	1896	wrl	semi-transparent version
8	blueCoilPole	19	4	332	wrl	tokamak part
9	blueCoils	47	8	748	wrl	tokamak part
10	blueCoils_transp	47	8	748	wrl	semi-transparent version
11	bulbs	3	1	0	wrl	common object
12	caps	19	3	0	wrl	tokamak part
13	caps_transp	19	3	0	wrl	tokamak part
14	circleForCoils	27	6	752	wrl	tokamak part
15	circleForCoils_transp	27	6	752	wrl	semi-transparent version
16	coilsCore	19	5	500	wrl	tokamak part
17	coilsCore_transp	19	5	500	wrl	semi-transparent version
18	core	21	2	24	wrl	tokamak part
19	core_transp	21	2	24	wrl	semi-transparent version
20	diagnosticWires	99	23	2928	wrl	tokamak part
21	diagnosticWires_transp	99	23	2928	wrl	semi-transparent version
22	door	18	4	180	wrl	external proto common object
23	dummy	1	1	0	wrl	help wrl file
24	dummy_transp	1	1	0	wrl	semi-transparent version
25	end	1	1	0	wrl	common object
26	femaleScrews	33	7	632	wrl	tokamak part
27	fly	1787	x	x	gif	animated gif
28	helpArrows	3	2	24	wrl	common object
29	helpTokamak	775	x	x	pdf	manual for the virtual scene

Table 5 - Files details part1

#	File name	Size (KB)	Size zip (KB)	Faces count	File type	Description
30	hollowChamber1	177	32	4502	wrl	tokamak part
31	hollowChamber1_transp	177	32	4502	wrl	semi-transparent version
32	hooks	76	16	1509	wrl	tokamak part
33	Infrastructure room -group of files	4144	x	1 752	x	inserted files from Petr Liska
34	interferometr	298	73	4554	wrl	inserted from Ondrej Grover
35	keyboard	3	1	12	wrl	room equipment
36	keyboard	21	x	x	jpg	texture
37	label	31	x	x	jpg	texture
38	mc	165	x	x	pdf	example
39	middleWire	162	30	3024	wrl	tokamak part
40	middleWire_transp	162	30	3024	wrl	semi-transparent version
41	mirnovCoils	24	5	552	wrl	tokamak part
42	mirnovCoils_transp	23	5	552	wrl	semi-transparent version
43	mirnovCoilsLimiter	16	4	392	wrl	tokamak part
44	mirnovCoilsLimiter_transp	16	4	392	wrl	semi-transparent version
45	monitor	5	2	60	wrl	room equipment
46	photoDiode	16	4	316	wrl	tokamak part
47	photoDiode_transp	16	4	316	wrl	semi-transparent version
48	powerCords	86	20	2448	wrl	tokamak part
49	powerCords_transp	86	20	2448	wrl	semi-transparent version
50	powerPoint	110	21	2144	wrl	tokamak part
51	rack	5	1	12	wrl	room equipment
52	rack	37	x	x	jpg	texture
53	redWire	59	8	1728	wrl	tokamak part
54	redWire_transp	59	8	1728	wrl	semi-transparent version
55	routes	6119	x	x	jpg	routes map
56	screws	72	14	1312	wrl	tokamak part
57	stairs	20	x	x	jpg	texture
58	stand	41	8	720	wrl	tokamak part
59	stand_transp	31	8	720	wrl	semi-transparent version
60	table	1	1	0	wrl	room equipment
61	tilesIn	15	x	x	jpg	texture
62	tilesOut	92	x	x	jpg	texture
63	tokamak	257	x	x	gif	animated gif
64	tokamakGolem	135	27	188	wrl	main file of the virtual world
65	tokamakGolem	15288	x		max	3Ds Max source file
66	thresholds	2	1	0	wrl	common object
67	verticalPoles	5	2	72	wrl	tokamak part
68	wall	41	x	x	jpg	texture
69	reference files	x	x	x	x	additional files

Table 6 - Files details part2

Chapter 8

Conclusion

In this chapter are presented several suggestions for future improvements of tokamak Golem VRML model and the conclusion of whole project.

8.1 Future work

The extension works on the project can be divided into two groups of which one is qualitative and the other is quantitative. Qualitative extension work will improve the quality of the model and enhance interactivity by improving on the existing structure of the program or its segments. Quantitative extension work will add new objects into the scene. It will not change the structure of the virtual world. This virtual world was designed with rooms for extension that effort by future researchers should focus on extending in quantitative way by adding multiple components to the main model.

The quality of the virtual model can be bettered by remodeling imperfect parts in the scene and by improving the code. The tokamak in the current virtual world is not very precisely modeled. During the modeling process the concern was to produce the best model in the given time frame. If considerably more time is devoted to the measuring of the device, more precise model can be created. Therefore the model can be qualitatively improved by creating exact digital copy of the device. Another possible quality improvement can be done to the code. Semi-transparency function for the parts of the tokamak was done after the project was almost complete. The buttons used to turn visibility and transparency on and off have just two states (on and off). It would be much easier for the user to have just one button with three states (on, semi-transparent and off). In other words, the transparency can be implemented in the better way and by using less code but the structure of the main file would have to be changed. Head up display has not been tested by users. User tests are very important to determine the usability of the interface. If the proper usability tests are done the HUD can be improved to be more intuitive and effective. The scene could be embellished by sound effects. They would make the world more vivid and likable. Sounds effects assigned to the interactive parts of the virtual world could help users recognize whether the interaction is successful (click sound when button is pressed or pumping sound when a part is pulsing). The possibilities of qualitative extensions are unlimited. Suggestions mentioned above are the most urging changes if qualitative changes are to be made.

The whole project is designed to be extended quantitatively. The current virtual scene of tokamak Golem contains only the most basic components of the device. The scene is prepared to be extended. It sets the environment for adding more objects into it. Adding new objects is easy and the functionality has been predefined. Quantitative extensions will make the overall model more complete and complex. Parts of the device can be added according the needs of professors. The number of tokamak parts is enormous and depends only on the level of details the modeler wants to achieve. There are prepared buttons for only fifteen new objects. This can pose limitations to the quantitative extending. If more objects were to be added, the structure of the HUD would have to be changed. Extensive work on adding new parts for the model is recommended.

8.2 Conclusion

The project is a new educational tool developed to help students to overcome the difficulty with understanding the complex device tokamak Golem. It is an unprecedented work created with no prior similar project to refer to. Bigger and more famous tokamaks have their own digital versions but Golem is not actively used for new research anymore and there is nobody who would pay for its digital visualization. Therefore this project is very important due to its uniqueness and it has great chance to become popular among people who are interested in tokamak Golem.

Virtual model of tokamak Golem fills the imaginary hole in the missing modern type of documentation for the device. It provides users with information about the tokamak. Virtual reality is more explanatory than commonly used teaching materials such as books and videos so it has a great potential as an educational mean. Interactivity of the model helps users to obtain the information they seek in an effortless way. The model also contains numerous visual data concerning the appearance of individual parts and location of respective parts of the tokamak in the context of the device. Moreover, it presents unique views impossible to experience in the real world, animations demonstrating the otherwise invisible phenomena and the feel of the device. Everybody will be able to access the model online from any place on Earth with computer and internet connection. That makes it suitable for becoming widely used by students and useful especially for foreign students. Professors can use the model as an explanatory material for their lectures in a more effective way than to use written examples.

The virtual model of tokamak Golem is accessible, user friendly, explanatory, demonstrative, relatively modern and unique. It is a useful educational tool with a great ability to be extended according the need of professors.

Appendix A – software, abbreviations, sources, references

Software used

- Autodesk 3Ds Max
- Autodesk Inventor 2010
- Adobe Photoshop CS5
- BS Contact
- Cortona 3D
- Fraps 3.4.2
- Microsoft Office
- VrmIPad 3.0

List of used abbreviations

3D – **3** Dimensional

CASTOR - **C**zech **A**cademy of **S**cience **T**orus

CD – **C**ompact **D**isk

CPU – **C**entral **P**rocessing **U**nit

CTU – **C**zech **T**echnical **U**niversity

FNSPE - **F**aculty of **N**uclear **S**ciences and **P**hysical **E**ngineering

FPS – **F**rames **p**er **S**econd

GIF – **G**raphic **I**nterchange **F**ormat

HUD – **H**ead **u**p **D**isplay

ITER - **I**nternational **T**hermonuclear **E**xperimental **R**eactor

JPEG or JPG– **T**he **J**oint **P**hotographic **E**xpert **G**roup

LOD – **L**evel **o**f **D**etails

PDF – **P**ortable **D**ocument **F**ormat

PNG – **P**ortable **N**etwork **G**raphics

RAM – **R**andom **A**ccess **M**emory

tokamak - **t**oroidalnya **k**amera v **m**agnytnykh **k**atushkakh (toroidal chamber with magnetic coils)

URL – **U**niform **R**esource **L**ocator

VRML – **V**irtual **R**eality **M**odeling **L**anguage (VRML means VRML 97 in the project.)

X3D – **E**xtensible **3D**

XML – **E**xtensible **M**arkup **L**anguage

Sources

All pictures and tables which do not have the reference were created by the author. Infrastructure room was modeled by Petr Liška. Petr Liška's room was slightly edited before inserting into the project. All the textures for the scene were made except **rack.jpg** [11]. Part of the code of the main file (buttons) was inspired by the work **ramcis2** [12]. The description of VRML was written in correspondence with [13-16].

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Appendix B – content of the CD

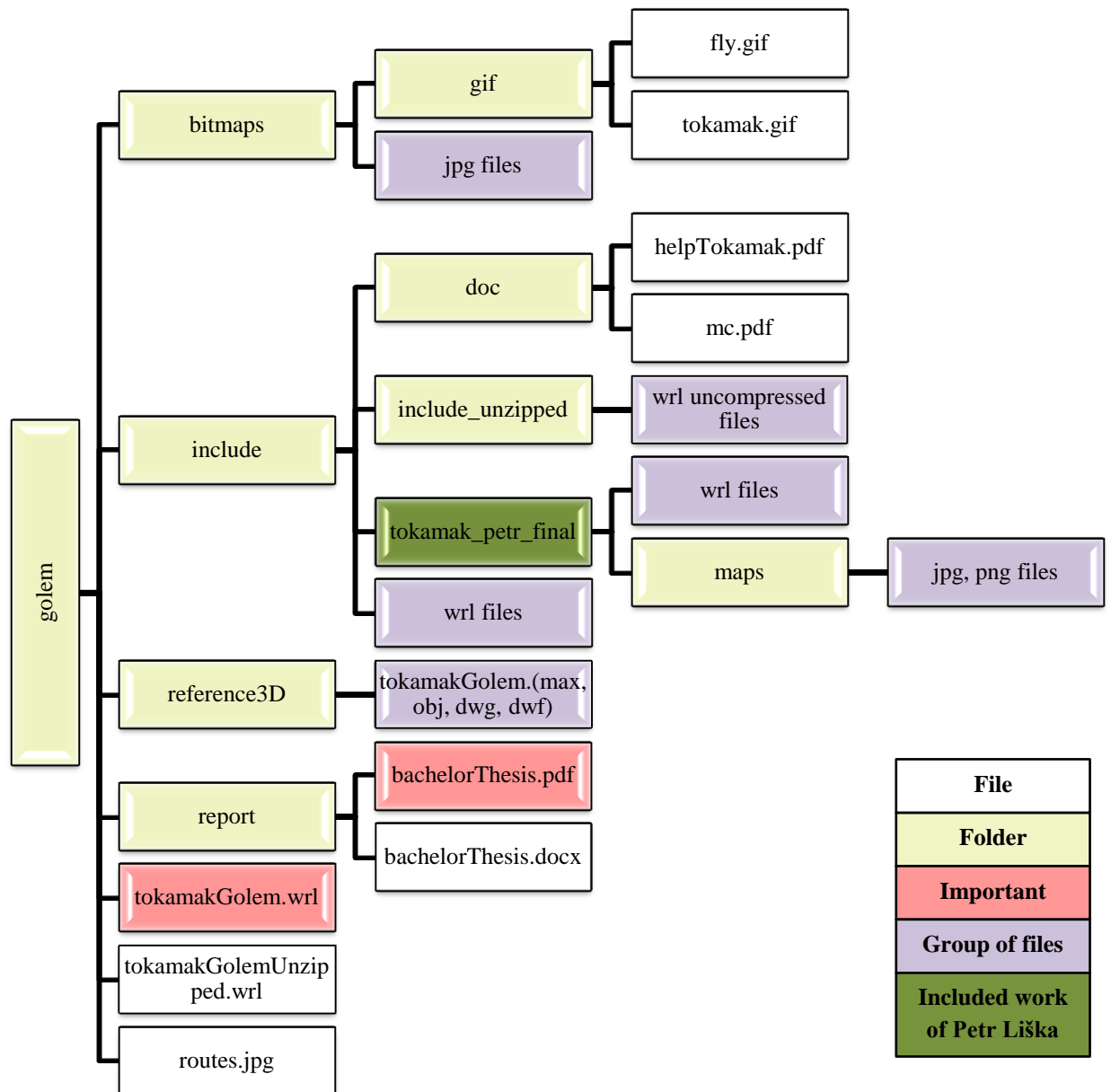


Figure 31 - CD hierarchy

The main file of the project is **tokamakGolem.wrl**. It can be opened by any VRML viewer. The report of the project is **bachelorThesis.pdf**. The manual to the virtual scene is **helpTokamak.pdf**