ISSN 1330-3651 (Print), ISSN 1848-6339 (Online)
UDC/UDK 004.771:[37.018.43:7.05]

THE DEVELOPMENT OF ASSEMBLY CONSTRAINTS WITHIN A VIRTUAL LABORATORY FOR COLLABORATIVE LEARNING IN INDUSTRIAL DESIGN

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Original scientific paper
This paper describes the development of assembly mate references within the Web-based Virtual Laboratory for collaborative learning in industrial design. Process concerns creation of basic geometric constraints for assembly work between distant students. It also analyses the combination of various software types for Computer-Aided Design and eXtensible3D for designing and creating multifunctional solutions. The designing procedures are illustrated by giving concrete examples. This way of working enables heterogeneous design applications to be used with faster generation of various design solutions. It proves to be efficient due to inability to work concurrently on the same assembly in real classrooms.

Keywords: *distance education, eXtensible3D(X3D), industrial design, mating constraints, virtual assembly*

Razvoj virtualnog laboratorija za kreiranje sklopova i pružanje podrške za kolaborativno učenje u okviru industrijskog dizajna

Izvorni znanstveni članak
U ovom radu opisan je način razvoja početnih orijentira za spajanje u Web-baziranom virtualnom laboratoriju za podršku kolaborativnog učenja. Proces se odnosi na kreiranje osnovnih geometrijskih ograničenja za kreiranje sklopova između udaljenih učenika u okviru industrijskog dizajna. U radu je prikazano kako se različiti CAD softverski paketi koriste u kombinaciji sa X3D tehnologijom, točnije kako se pojedinačni dijelovi modelirani uporabom različitih paketa sklapaju u zajedničkom okruženju. Proces dizajniranja okruženja i njegovih funkcija opisan je kroz konkretan primjer. Laboratorij omogućava uključivanje u zajednički rad više heterogenih klijenata, kao i brzo generiranje različitih dizajnerskih rješenja. Uporaba virtualnih laboratorija za kreiranje sklopova pokazuje se efikasnim čak i u realnim situacijama u kojima nije moguć istovremeni rad na zajedničkom rješenju.

Ključne riječi: *eXtensible3D(X3D), geometrijska ograničenja, industrijski dizajn, učenje na daljinu, virtualni sklop*

1 Introduction

Computer laboratory exercises are essential part of engineering education. The laboratory improves students' understanding of fundamental concepts about data analysis, problem solving, and scientific interpretation. Mostly, such laboratories are either inaccessible or unable to meet the users' requirements entirely. The solution to the problem relies in creating virtual laboratories, which then can be used as a supplement or exchange of certain courses, enabling virtualization of real exercises or overcoming the limitations of real environments.

Industrial design refers to those activities involved in creating the look of the product, deciding on the product's mechanical architecture, selecting materials and processes, and engineering the various components. Using Virtual Reality (VR) technology industrial design can be performed within Virtual Environment (VE), which shortens design and development time. Thus, industrial design shares the characteristics of VEs (e.g. collaboration) and in the form of Virtual Design (VD), becomes applicable in engineering courses. It aims to enhance the validation of product concepts via advanced simulations, to increase the efficiency of component and material reuse in different life cycle phases, and to reduce simulation costs.

Many synonyms such as virtual engineering or virtual assembly are related to VD. Virtual engineering means simulating various engineering activities, such as assembly, production-line operations and machining within a predefined VE. Virtual assembly concerns setting up a product model in which users can check and modify the configuration and material properties of an assembly in a VD space or VE [1]. With the integration of Computer-Aided Design (CAD), Computer-Aided Manufacturing (CAM) and Computer-Aided Engineering (CAE) systems, sophisticated geometric models can be analysed in a VE. Using computer analysis, users can estimate product model and do data description and visualization, then make assembly related engineering decisions, without the need for a physical model to support estimations. Such environments become very important part of analysing products which are not easily accessible in real environment [2].

Tool support has a significant role in the successful implementation in designing products. Possible integration of its functions (e.g. assembly techniques in VE), creates high-quality laboratories, which can be used, not only for practical exercises in distant education, but also to overcome excessively high expenses (assembly costs) in training.

Very important assembly parts are geometric constraints, such as tangency, colinearity, parallelism, perpendicularity, coincidence, symmetry, etc. They impose a relationship between geometric features. Assembly constraints can be applied on faces (circular or rectangular), lines and points as parts of work geometry. Mate constraints assemble components face-to-face or adjacent to one another, usually removing three degrees of freedom, one linear translation and two angular rotations between planar surfaces. A coincident constraint assembles components face-to-face (same translation and rotation) or adjacent to one another. An angular constraint assembles faces at a specified angle to define a pivot point. Tangent constraint assembles faces, planes, cylinders, spheres, and cones to contact at the point of tangency. Tangency may be inside or outside a curve.

Although most CAD programs have modules for collaboration, there is no simple exchange between them. Our idea is to use X3D (eXtensible 3D) as the suitable standard for the exchange. Using X3D we created Web-based Virtual Laboratory called VirCADLab aimed for practical exercises in industrial design. The lab is used as a universally designed environment for collaborative design enabling involvement of various software packages in creating parts, but using only one space to assemble them. VirCADLab also integrates heterogeneous clients, allows concurrent work on creating final solution, helps learning design in practice at distance, and enables group exercising and testing. All this provides faster generating of various architectures (models) and enriching distant learning experience in the Department of Engineering Management at Singidunum University, Serbia, Belgrade.

The rest of the work is organized as follows: section two describes VR technologies, classrooms and universities as well as solutions similar to ours; section three contains creating environment and implementing functionalities in virtual laboratory; section four presents how environment works with mate references; section five explains process of virtual industrial designing at distance; and finally section six concludes and presents the future work.

2 Related work

Web technologies promise many 3D applications in simulation and training, making users directly participate in and explore environment. An excellent survey of 3D Web technologies is given in [3]. The most commonly used are X3D and WebGL (Web-based Graphics Library), both designed for the creation of interactive Web-based and broadcast-based 3D content. WebGL works without installing additional software, but only within a compatible Web browser. Regardless of the fact that X3D works at much lower level and needs installation of an appropriate plug-in, it works within any Web browser, employs a scene-graph, specifies a declarative geometry definition language, a run-time engine, and an application programming interface which provides an interactive, animated, real-time environment.

Most CAD programs possess the modules for assembling and collaboration with other departments in the context of monitoring, development and product life cycle [4]. Integration of VR system with CAD has been presented in [5]. Many solutions related to distributed and collaborative virtual prototyping, interactive design visualization systems, virtual design framework for product customization, and design and manufacturing simulation of mechanical products are presented in [6]. Also, there exist solutions using X3D for creating virtual assembly laboratory. The VIEW project [7] describes great course for engineering students using virtual assembly techniques, but without mating constraints, collaboration, text or video chat. From the same authors, an excellent educational environment is presented in [8], which combines X3D and SolidWorks in creating assembly, but lacks group-work support. Research in paper [9] is an excellent interface with many functions enabled, but also lacks group-work support and shared assembling functions.

Solutions [7, 8, 9], because they use combination of CAD and X3D in creating students' applications (or as such can be used), are served as the basis for our further research and development. With respect to all, our proposal eliminates some of the disadvantages of previously mentioned engineering VEs, such as concurrent assembly work with the possibility to create parts using different applications, applying it all in distance design exercising, learning and testing. Our goal was to incorporate as many CAD software features in the existing shared environment as possible.

3 VirCADLab model and components

VirCADLab is a shared virtual environment, which students use as 3D Web interface. In order to enable collaborative students' work in such environment, the lab consists of Virtual Client Screens (VCS) visible to all participants. Participants are scattered remote students' computers. They access the lab from their own home computers, and start programs or applications on any VCS in the environment. Very important components which connect real and virtual computers are Virtual Machines (VMs). Virtual Network Computing (VNC) is the default protocol for accessing client VMs, making them platform independent.

VirCADLab has integrated VNC client software, which provides direct connection with VMs in VM repository. VMs with different characteristics can be used in the laboratory, and they could be used for student interface or services. The development process for a new VM consists of creating a new one, installing an appropriate operating system and software, and configuring it. The model with components is presented in Fig. 1.

Collaboration between distant students in VirCADLab is realized using BS Contact X3D viewer and BS Collaborate server [10]. These software tools work as a server-client pair to support visual collaboration. BS Collaborate Server is a networked communication platform that supports interactions in collaborative VEs (text chatting, server side computation and client identification mechanism), shared events, shared objects, and locking. BS Collaborate works together with the BS Contact client which is a viewer of X3D scenes. It is used for presenting information of VirCADLab and server side, receiving all kinds of action interaction from users and lab, and returning the various operations, interactions and communications of users to the server side. BS Contact can make lab a part of the HTML page and then share the environment between students. BS Contact enables displaying Adobe Flash movies within the scene. This feature was crucial to our solution, and it is described in the next section.

4 VirCADLab implementing functionalities

This section presents the implementation of the basic VirCADLab functions. In this example, five different CAD programs are being used for the creation of assembly parts (AutoCAD, CATIA, Inventor, Pro/Engineer (Pro/E), SolidWorks). Parts had to be exported to a uniform format. Chosen software packages are among the most commonly used CAD packages, and they either have built-in X3D or VRML export feature or use plug-ins and translators. VRML is X3D predecessor which can be easily imported into X3D scene.

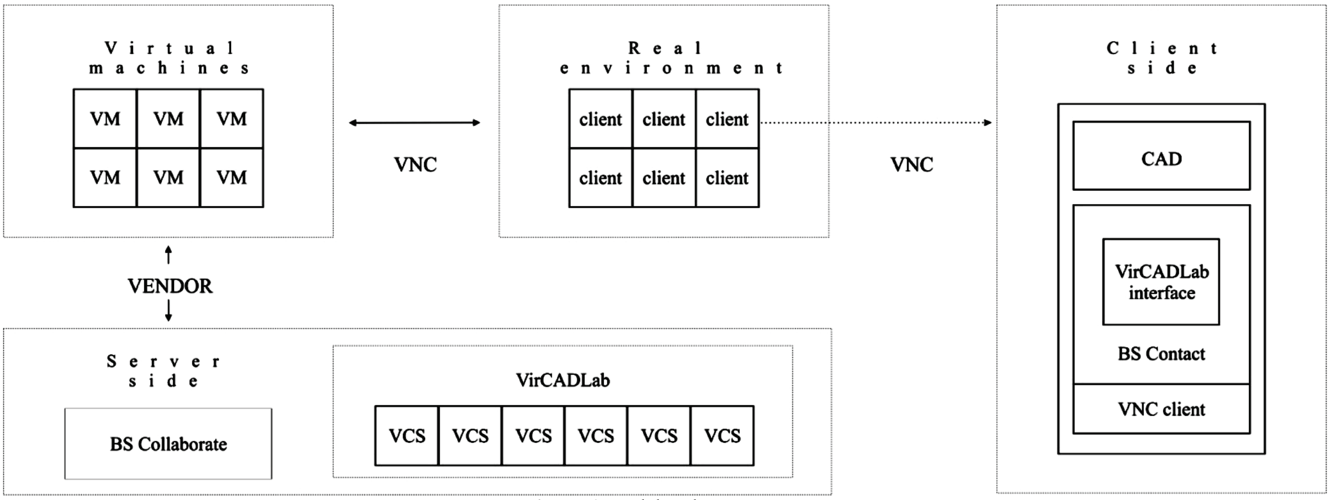


Figure 1 Model and components

In order to enable visibility of all the screens in VirCADLab, and work on individual parts from the lab, we use capability of X3D node called MovieTexture node to support Flash movies. It defines a time dependent texture map, and the URL field defines the movie data support within the environment. The MovieTexture node can be referenced by an Appearance node's texture field as a movie texture for displaying streaming media. More about the X3D nodes can be found in the X3D specification [11].

Connections with VMs over the MovieTexture node are realized using FlashVNC client. This combination enables display and use of various applications within the same environment. It is also possible to integrate different applications, useful educational resources, which was discussed in [12]. Organization of nodes, relationships, use of mate references, and the final assembly work are shown in Fig. 2.

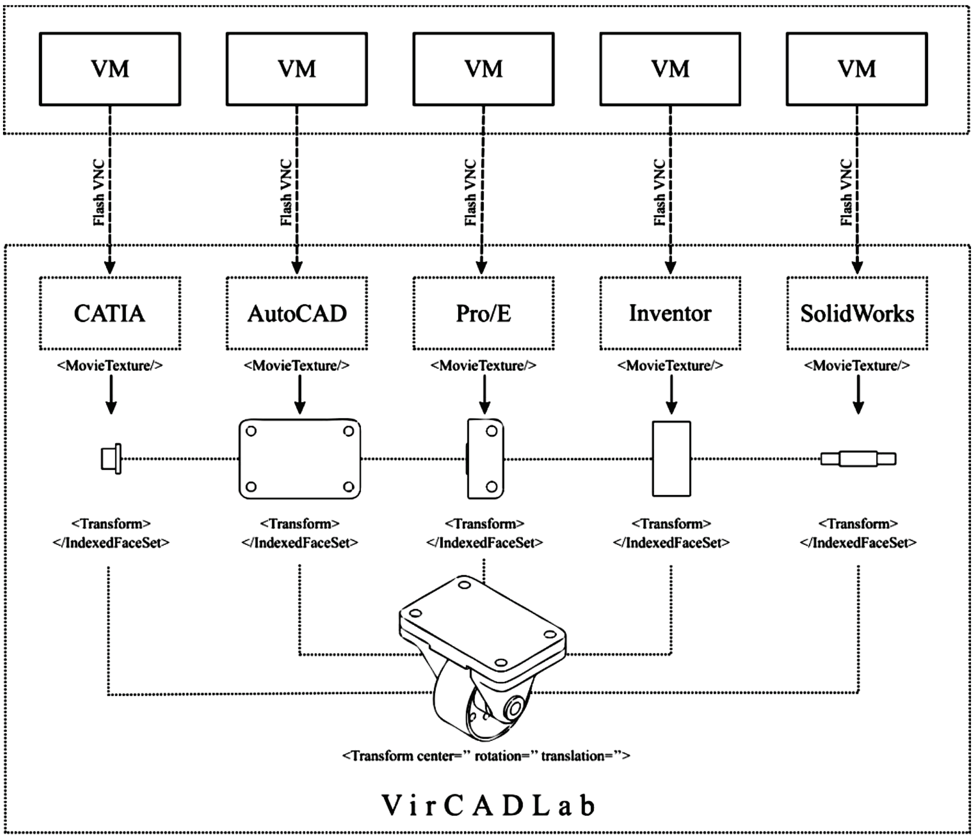
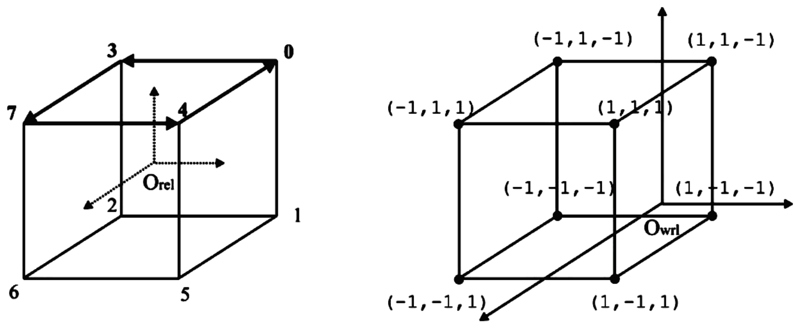


Figure 2 Organization of nodes and the final assembly work

4.1 Characteristics of X3D geometry nodes

Defining geometry in X3D is accomplished using various nodes, such as CADPart, CADAssembly, Shape, IndexedFaceSet, IndexedLineSet, Box, Sphere and many similar. IndexedFaceSet is the most commonly used node for creation of shapes, polygon by polygon (point by point), allowing a highly compact representation of the vertices. The specific attribute of this node is the "Coordinate" field, which enables a vertex to be used many times. The "coordIndex" specifies a list of coordinate indexes defining the faces to be drawn. To separate the indexes a marker "−1" is used, which indicates that the current face has ended and the next one begins.

For further functionality implementation, especially important is Transform node, with its "rotation", "center" and "translation" attributes. This grouping node defines a local or relative coordinate systems for the children nodes, defined in terms of transformations from ancestor coordinate systems. Generally in 3D, not only the amount of translation or angle of rotation must be specified, but also the axis of translation and rotation. Creating a cube in X3D using IndexedFaceSet node as well as the world coordinate system (Owrl) and local coordinate system (Orel) is shown in Fig. 3.

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<IndexedFaceSet coordIndex='0 1 2 3 -1, 4 7 6 5 -1, 0 4 5 1 -1, 1 5 6 2 -1, 2 6 7 3 -1, 4 0 3 7 -1 '>
<Coordinate point='1 1 -1, 1 -1 -1, -1 -1 -1, -1 1 -1, 1 1 1, 1 -1 1, -1 -1 1, -1 1 1 '/>
</IndexedFaceSet>
```

Figure 3 Using IndexedFaceSet node in X3D

The conversion process from CAD to X3D results with all parts grouped as IndexedFaceSet nodes with predefined Transform node and its "translation" and "rotation" attributes. This node is essential for data exchange and it is only reference which can be used for further creation of mate connections. Copying attribute values from one node to another and using geometrical constraint functions within the Script node, sets the position of the related objects.

4.2 Using nodes for creating mate constraints

With the exception of the torus, every primitive solid has a form expressed in terms of quadratic and linear arithmetic equations. This makes it attractive for creating constraints solutions. The basic steps in creating mate constraints in X3D include the following: objects detection, face selection, equalling values, mate constraints and additional adjustments.

4.2.1 Object detection

Before defining constraint functions, it is necessary to determine on which two objects in the scene specific mate operation will be applied. Because the first objects parameters will match the second, it is also important to detect the order of selection. The detection was made difficult, especially detection of the objects' sides, due to the fact that all CAD programs export X3D files only as a group of IndexedFaceSet nodes.

Face detecting is made by listing and grouping IndexedFaceSet values taking into account digits up to "−1". If there are four digits prior to the first "−1" digit, the shape is a rectangular form. Circular surfaces (e.g. cylinder shape) are represented with 18 points. Work on extracting is the same for rectangular, circular or even triangular shapes.

Each time a mouse event occurs (selecting object), process continues with using a TouchSensor attached to the part with a Script handling this event to track the mouse position. Then, "routing" events to a Script, it receives the "hitPoint_changed", and stores its value into a field. When Script receives the "touchTime" event, it retrieves the stored value which can be sent to the Transform "centre" attribute (that handles the relative coordinate system (Orel) value). But, the returned value is determined and depends on world coordinate system (Owrl) and that affects Orel to be placed far away from the object. This is why additional calculations are necessary.

4.2.2 Face selection

Selecting objects' faces is a function which includes setting the coordinate system at selected place by finding the centre of the object. This needs to be done for faces of both objects, depending on geometric constraint, especially in the case of classic mating (face to face). The first step would be to determine the centre T of both faces, and then place relative coordinate systems (Orel) at the point T. In the previous step (Object detection) Orel is placed at the last mouse position (which, in most cases, is far away from the objects' face), but using the coordinates can help determine the centre of the selected face.

First, after occurred mouse event and the information about coordinates passed, the closest triangle or a quadrilateral near selected face extracts in the form of three or four digits (coordinate points). Using two diagonal lengths and calculating the distance of two points in space, determines the centre for quadrilateral objects. For irregular triangles, first calculated are sides' centre coordinates, and the median is required on their intersection. For irregular polygons, first step is to determine the centre of every side, and then based on these medians their intersections are defined. For a circle constructed with 18 points, the centre is determined with diagonal half (first to tenth point). After necessary calculations, Orel is placed at point T, but because of the default values (0 0 0) of Orel, which are not compatible with point T (its values depend on the world coordinate system), Orel equates to Owrl, and then to point T. Adjustments of Orel are the most important step and depend on the adequate construction geometry type.

4.2.3 Equalizing values

After setting and equalizing the coordinate systems of both objects, and by clicking on MATE button, objects are placed at the desired position, to the given coordinate systems ($x_1 = x_2$, $y_1 = y_2$, $z_1 = z_2$). Equalization means taking attribute values "rotation" and "translation" of the second selected object and assigning these values to the first selected object. In this way faces are placed in an identical position, and further adjustments are possible with the help of menu options.

4.2.4 Mate constraints

Equating the coordinate systems solves the coincident case and based on the geometrical constraint equation used in computer graphics, defines the relationship between faces (distance and angle) as well as other constraints (parallel, tangent, concentric and perpendicular).

Distance is determined by moving coordinates of the attribute "translation" of the first selected object, while the rotation is determined using the same principle, changing the values of some coordinates "rotation" attributes and entering degrees value. Since X3D measures angle in Radians, automatic conversion of input is done.

Parallel (2 planes or a plane and a circle) is determined similar as distance with an addition a normal axis is chosen. The case of parallel faces involves equalizing orientation of the two objects and making unequalled only one axis (position). Parallel objects are accomplished by equalizing orientations of the two objects and equalizing two axes that do not form an angle of 90°. Perpendicular is set also by selecting the appropriate axis.

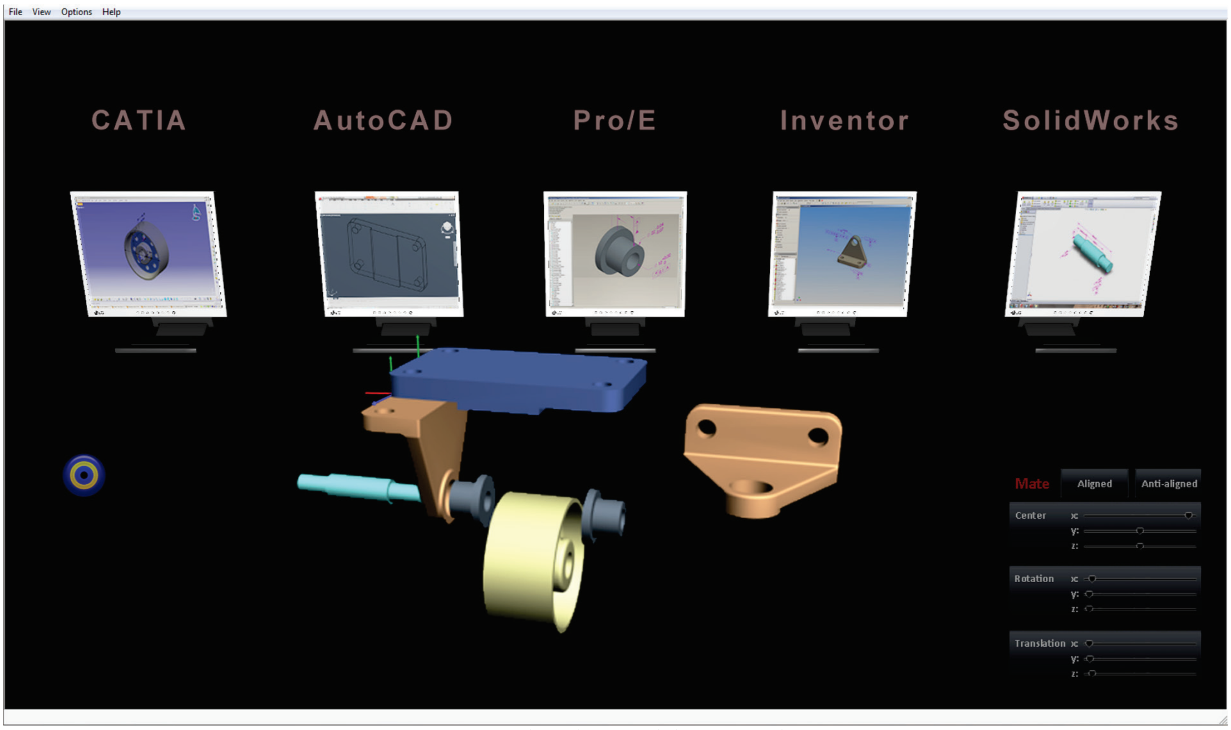

Figure 4 Using VirCADLab in group project

Concentric constraint is defined between two circle areas. Creating a cylindrical shape means that the centreline axis or relative coordinate system (Orel) is in the middle of the object (default value 0 0 0). Particularly this process facilitates elimination as much of the first step, because there is no need for previous calculations between Orel and point T. With additional options, Orel could be modified before mating (horizontal or vertical placing of the object).

Tangency (one plane and one circle, or two circles) solves in several ways (depending on the objects, whose recognition is performed in the first step). For a circular shape it needs to determine the longest diagonal (when it comes to ellipse), and take the half of the diagonal value as value passed to the "centre" attribute, x or y axis (depending on the object's position). Polygon centre, as described in the first step, determines the face's central point (T). Two circular areas are identified by the values of half the diagonal and moving the x axis (the vertical cylindrical shape) and y axis (the horizontal cylindrical shape). Tangency between the two circular surfaces (cylinder shape) is determined by half of the both diagonal values and passing that value to "centre" attribute x axis (for vertical cylindrical shape) or y axis (for horizontal cylindrical shape).

4.2.5 Additional adjustments

In the case that the program did not recognize the designer's intent, it is necessary to allow additional adjustments. Additional adjustments are possible using a "center" slider displayed in the lower-right corner of Fig. 4. After that, equalization with the object's relative coordinate systems is performed, by "routing" to the "center", "translation" and "rotation" attributes. Options "Aligned" and "Anti-aligned" work properly only for alignment conditions, not always for the cylindrical. Aligned is when the angle between the directions is 0°, and anti-aligned is when the angle between the directions is 180°. Described constraints and options are applied in the same way on lines and points, using IndexedFaceSet coordinates as references (two for lines and one for point). Constraints are also made using points and lines, points and areas, or lines and areas as references.

5 Process of virtual industrial designing using VirCADLab and evaluation

Industrial design courses are attended by many small groups of 5 to 6 students, who work closely with experienced mentors on a design project. Every group is conducted by one VirCADLab instructor or mentor. Laboratory instructors are professors or postgraduate students (MSc and PhD) that have a strong background in industrial design. Individual instructors assign grades for all students in their section. Instructors collaborate to ensure that there is equitable grading between lab sections. First part of the total grade is based on individual and collaborative work within the lab, and second on examination. In lab students discuss the regularity and quality of completed parts of the final product and thus come to the correct answers during examination.

Students are previously introduced to the product development process, which includes:

- Previously organized and accomplished VR course in technical documentation reading and understanding
- Previously organized and accomplished one of five CAD modelling VR courses
- Drawing based modelling.

Prior to work in a virtual environment, students were introduced to the basics of engineering, basic rules of design and technical drawing, as well as creation and follow-up of technical documentation. Based on the above, students were able to read technical documentation related to a given element (subassembly) and they were able to model given parts in a CAD program of their choice. After that they begin product assembly with defined constraints in collaboration with other participants in the virtual environment. The designed assembly will indicate that it is valid in terms of geometry and kinematics, and eventual mismatch will be shown as an accompanying text, from which they can conclude what is wrong and how it can be repaired.

In industrial design courses students pass their exams theoretically and practically. Examination includes assessment of the implemented assembly, grading part modelling (practical work) and answers to questions (theory). Based on drawing, students assess mate reference while accomplishing the theoretical part of the exam at the same time.

Results of practical work are more than satisfactory, due to the fact that working in a group ensures that every member has to satisfy given criteria; otherwise it will influence the entire assembly. Also, compared to students who attended traditional class, test results are much better because the models and assemblies, and especially the constraints have enabled faster understanding and problem solving, hence, giving correct answers. An average grade for students traditionally taking the exam was 7,7, while the average for student using virtual classroom was 8,3.

At the end of the course, students were asked to complete a simple survey about their experience with VirCADLab. The statements were written one phrased positively and one phrased negatively, and students were asked to rate their compliance with each statement on a scale of 1 to 5. The statements and answers are presented in the following table.

Table 1 Student feedback on usability of the VirCADLab in group project

	Question	Mean	St. deviation
1	I think that I would like to use VirCADLab more frequently	3,6	1,35
2	VirCADLab is very complex and complicated system	1,4	0,97
3	I would like to use VirCADLab for contact with students and professors	4,3	1,06
4	I think that I would need support from a technical person to use the system	1,5	0,71
5	I found that this way of learning is very interesting	4,0	0,94
6	I think that this way of learning is not appropriate for this type of course	1,6	1,07
7	I think that mastering the basic functions of the system is intuitive	4,3	1,06
8	I found virtual environments disorienting	2,1	1,37
9	I understood the VirCADLab functions and adapted to the group work very quickly	4,2	1,14
10	I needed to learn a lot of things before I could get going with VirCADLab	1,9	0,95

Questions 1 and 3 (opposed are 8 and 6, respectively) and their answers helped assessing the readiness of students to use the virtual system. These questions help us to conclude whether the environment is sufficiently attractive, and also if students are ready to research and use virtual systems in the future. Even though it is practically the end of the course, the assessment is a very important part; if unsuccessful it could downgrade the whole system. In order to gain information about classroom usage in other courses, the questions help in obtaining answers whether and how this is possible. Questions 5, 7 and 9 are included to assess if students had problems in using and mastering the system, because if the environment is not intuitive and students are interested to study the system, this might lead to students dealing more with the problem of virtual environments instead of issues defined by the course. Questions 5, 7 and 9 are coupled with questions 2, 4 and 8 and give us answers concerned with mastering the VirCADLab interface.

6 Conclusion and future work

In this paper we proposed a method for creating basic geometric constraints within the virtual laboratory. The proposed method combines various types of CAD programs and X3D technology for concurrent assembly work between distant students. The advantage of this method is in student's participation in simple projects without any extensive knowledge from relevant fields and they can also contribute to problem solving. In this way, students visually study and specialize, what is the reason for the use of simpler and less demanding projects. Besides, the proposed method has a faster generation of various models. The weakness is reflected in the use of simple constraints, but the idea is to introduce more complex constraints into the virtual environment as students gain certain knowledge.

Further integrating and developing as many CAD functions within the VirCADLab as possible is our main goal. Also, our future work will be directed towards exporting drawing files from virtual assembly lab and link these with all previously created parts (associative attribute of all CAD programs). All mentioned functions could be extended to haptic-enabled tools or CAVE system for sharing, learning, and testing.

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