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## **Development of a novel 3D simulation modelling system for distributed manufacturing**

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### **Abstract**

This paper describes a novel 3D simulation modelling system for supporting our distributed machine design and control paradigm with respect to simulating and emulating machine behaviour on the Internet. The system has been designed and implemented using Java2D and Java3D. An easy assembly concept of drag-and-drop assembly has been realised and implemented by the introduction of new connection features (unified interface assembly features) between two assembly components (modules). The system comprises a hierarchical geometric modeller, a behavioural editor, and two assemblers. During modelling, designers can combine basic modelling primitives with general extrusions and integrate CAD geometric models into simulation models. Each simulation component (module) model can be visualised and animated in VRML browsers. It is reusable. This makes machine design re-configurable and flexible. A case study example is given to support our conclusions.

**Keywords:** simulation modelling, VRML modelling, connection features, virtual manufacturing.

### **1 Introduction**

Manufacturing enterprises face a number of overarching challenges: lowering the cost of production, reducing lead-to-market time, and finding the means to incorporate a set of globally

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distributed partners within a distributed manufacturing environment. It has shown how these challenges would be met effectively through the use of a more modular and reusable approach [1,2,3] in machine design, testing, and implementation, and the use of a Web-based information system [4,5,6]. Ideally, each module of a machine design should be rapidly verified with errors and misconceptions identified as early as possible and a whole machine as an assembly of various modules should then be analysed and tested virtually before being physically implemented. Although various CAD/CAM systems are now widely used, properly integrated approaches to machine design and control are still in their infancy and have not yet been established in industry [7]. It is believed that integrated 3D geometric simulation and emulation techniques can be applied to the optimisation of machine design and control logic testing. Although machine designers and control system implementers are making use of isolated simulations [8] for the optimisation of machine design, e.g., motion simulation, and for control logic testing, e.g., discrete event simulation, such isolated simulations could not support consistent modular and reusable machine design. Recent studies [9,10] indicate that a visualisation and simulation system might have the Internet as its backbone and Web technologies such as Java, HTML, VRML, TCP/IP and Agents could be applied as its communication infrastructure, because a Web-based system has a universal interface, uses open standards, and is globally supported.

This paper focuses on the development of a novel 3D simulation-modelling system for supporting distributed modular manufacturing. It allows a machine control system to be decomposed into a set of distributed components associated with different machine modules. It makes the control logic an integral part of module design and machine design and allows the remote visualisation of machine (or module) behaviour over the Internet by geographically distributed engineering partners. Such remote visualisation is firmly supported by modular simulation models developed within this system.

In this system, we classify simulation models into two categories: module simulation models and machine simulation models. In order to create these two types of simulation models simply and easily, new concepts of drag-and-drop assembling and connection features (unified interface assembly features) are introduced in the system to develop two modelling tools, namely module creator and module assembler. With these tools, designers can rapidly create module simulation models integrated with control logic and interface assembly features. They can simply assemble these models in a drag-and-drop manner.

Following this introduction, related work is briefly reviewed in Section 2. The prototype system structure and design are given in Section 3 and 4. A case study example is discussed in Section 5, and finally conclusions are drawn.

## **2 Related work**

In our distributed applications, any complete machine is defined in a hierarchy in terms of systems, sub-systems and modules. Each system consists of one or more sub-systems that are each in turn made up of modules. The modules represent physical sub-assemblies of the machine containing one or more elementary parts associated with motions and control logic and have VRML simulation representations. Correspondingly, machine models are hierarchically made up of module models. In this paper, we use a module or a module model to mean the same virtual representation (model) of physical module.

Our distributed application system uses the Internet as its backbone and Web technologies such as HTML, VRML, and TCP/IP as its communication infrastructure structure (Fig. 1). A machine and its control system design developed in the process definition environment (PDE) [7] are located in the application server. Through a Web server, they can drive the real machine in the workshop and the corresponding virtual machine (a VRML simulation model) in its client windows. Design and development of a rapid 3D simulation modelling system is the focus of this paper.

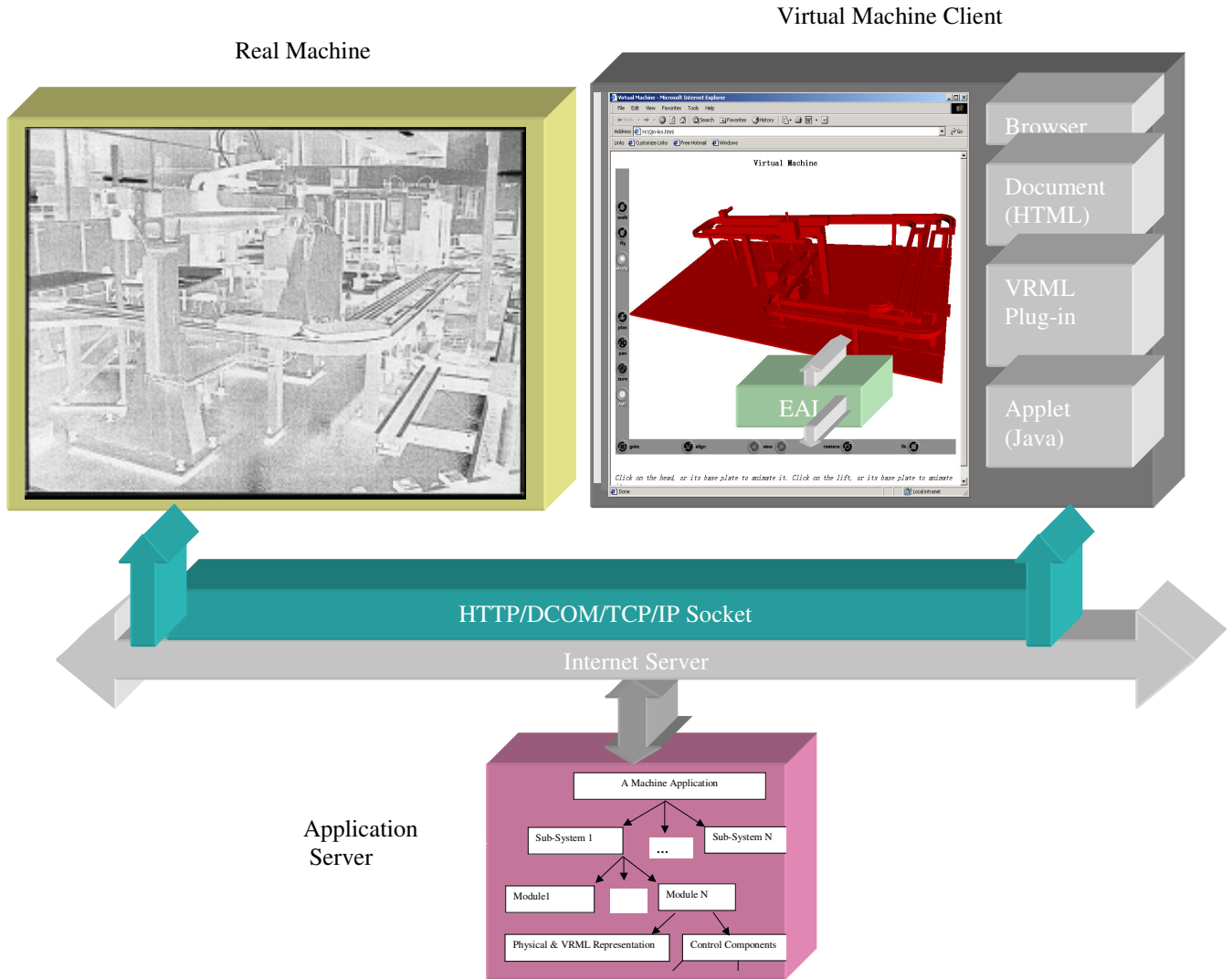


Fig.1 Application system structure

Three-dimensional simulation can be broadly classified into two categories: motion simulation and control system simulation. Motion simulation can integrate CAD designs for mechanical systems with 3D simulated dynamics/kinematics motions to see how the designs will perform. The simulation models can be developed with commercial CAD packages, e.g., Pro/MECHANICA [11] or Working Model 3D [12]. For example, one can import full CAD assemblies into a Working Model 3D system, and then add springs, dampers, pin-joints, forces, and a variety of other constraints, e.g., key-frame positions of moving parts, to create motion models. These models can be viewed as animated graphs and 3D bodies. Obviously, developments of a module simulation model within current CAD systems involve creating various

CAD parts based on design features, creating CAD assemblies based on low-level assembly constraints such as mate and align, and creating motion specifications based on the assemblies. It is a time-consuming process and simulation models have no relations with control logic.

For control system simulation, the Virtual Workbench system described by Weyrich and Drews in [13] used the professional modelling tool, Multigen II, for pre-processing of CAD data and creating VRML-based simulation models by producing object hierarchies and levels of detail, processing geometric objects and adding colour, material and texture to the objects. Unfortunately, this system required an intensive manual pre-processing procedure. The use of VRML-based simulations for virtual manufacturing applications has become increasingly important. In order to build up VRML-based simulation models, CAD models in [14] from various CAD packages were first translated into the International Graphics Exchange Standard (IGES) form, and then translated to VRML files. Finally, a VRML editor was used for making an assembly for animations. However, it was found that development of the VRML model in that way required formidable effort and time, for example, if a part was modified in the CAD packages, the engineers had to export the CAD models to VRML files again for re-assembly. Actually, when a CAD model for a part or an assembly is exported to a VRML file, primitive objects in the model will follow a flat hierarchical order. The objects will also be described in a set of polygonal facets in a global co-ordinate system. Therefore, the various primitive objects become inaccessible individually and the final VRML file may become too big to be suitable for distributed applications. It seems clear that using and converting CAD data into simulation models is a time-consuming procedure. Some efforts [15] were made to develop Web3D creation tools, such as *AC3D* and *mjbWorld*, in order to easily create VRML-based [16] 3D visualization models. But, they did not facilitate the assembly of modules.

### **3. Hierarchy of the simulation models**

In our system, we divide simulation models into two types: module models and machine models. A module simulation model is a virtual representation of a physical module to demonstrate a modular design's motions, functions, control logics, and geometric appearances. In addition, a module model is associated with possible connections (defined by unified interface assembly features) with other modules. A machine model may be a sub-system model or a system model assembled from module models.

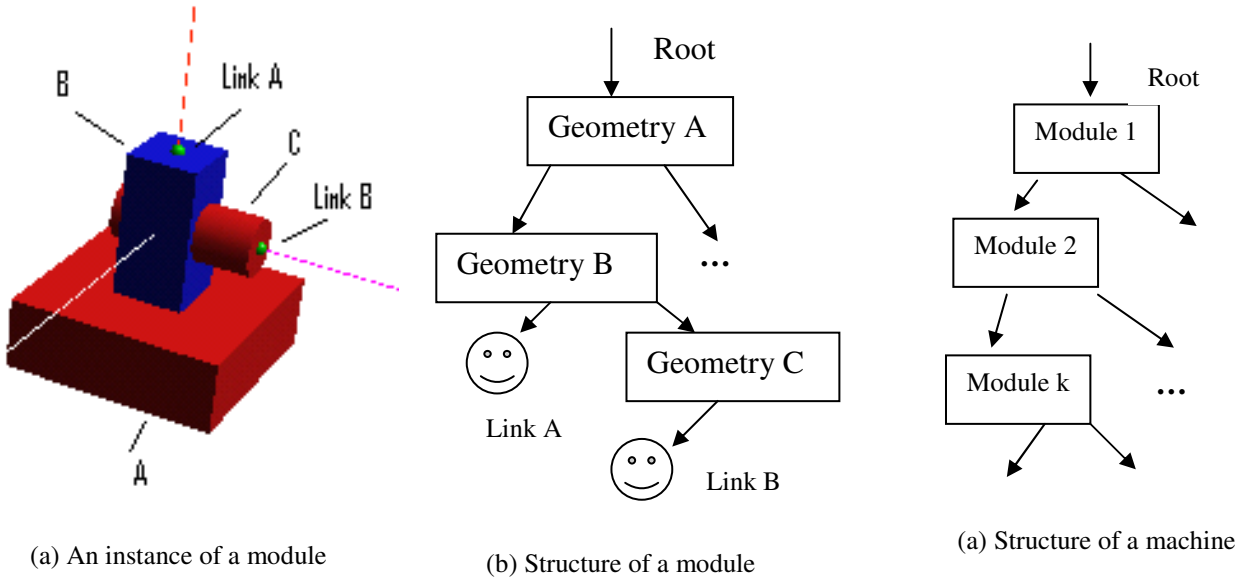


Fig. 2. Hierarchy structures of the simulation models

A module model is visualised as a 3D simulation model and is represented as a tree structure. It is built with various elementary geometry such as cylinders and boxes in a hierarchy way. An elementary geometry is defined in a local co-ordinate system (LCS). Its position and orientation is defined with respect to its parent's geometry. Motion with an elementary geometry can be defined in its own LCS. An elementary geometry not only can have other elementary geometry as child nodes, but also can have some pre-defined connections as children. A connection is represented as an attachment point associated with assembly constraints with respect to another module's model. For instance, a module (Fig 2(a)) can be modelled from the

Base geometry A. The Base has a child of the geometry B (Slide), which can move on the top face of the Base. The Slide has a child of the geometry C (Shaft), which can rotate about its axis. The Slide also has a connection “Link A” at the centre of the top face, which links to a module “A”. The Shaft has a connection “Link B” as well, which links to a module “B”. Connections are geometrically represented as small spheres. The corresponding hierarchy structure is shown in Fig. 2 (b).

A machine models can be defined by assembling module models in a hierarchical tree structure (Fig. 2 (c)). A child module model can be assembled in a drag-and-drop manner. The system will automatically match connections between the child module model and its parent module model, and compute the assembly position of the child module with respect to its connected geometry in the parent module. Comparing with traditional CAD assembly featuring low-level constraints such as mate and align, this assembling process is simple.

#### **4. The system design and implementation**

The prototype system is a Java application. With it designers can rapidly create module simulation models and assemble them into machine simulation models. The models can be viewed as wireframe models in a Java2D window [17] and viewed as 3D rendering models in a Java3D window [18]. The animated models can be checked in an embedded VRML browser. In our modelling system, both VRML and Java3D were used to represent simulation models. VRML formatted models are employed for the Web-based visualisations through a suitable VRML Plug-in, e.g., Cosmo Player. The VRML models can be embedded into a HTML file. The logic engine on the Web server can drive the simulation model remotely by Java Script nodes in the HTML page through the VRML EAI interface mechanism (Fig. 1). Java3D-based native simulation models are used for building up simulation databases, because they are easy to maintenance and their sizes are small. Internally, both models are derived from the same structure.

## The modelling system structure

This simulation-modelling tool has been developed using Java™ 2 SDK with Java3D. Its interface is implemented using the JFC/Swing GUI components. These components can customise a look and feel without relying on the native windowing system, and simplifies the deployment of applications. The interface includes an application window, three pull-down menus and a bar of icon menus. It also has a modelling tree window for displaying hierarchy nodes and three tabbed windows (Java3D, Java2D and VRML browser). The interface is shown in Fig.3. It is simple and easy-to-use.

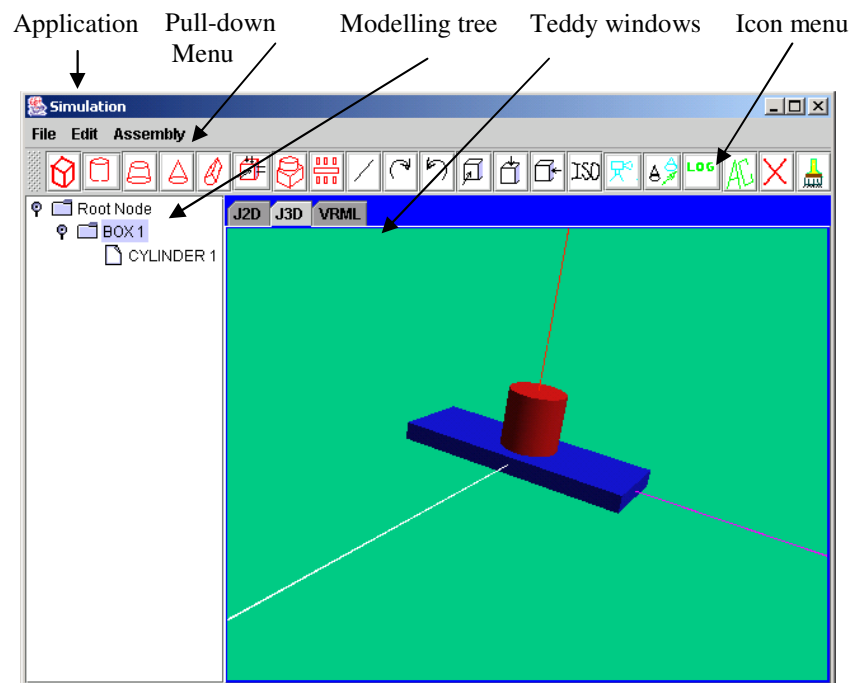


Fig. 3. Interface of the modelling tool

## 4.2. Creating module simulation models

Creating module simulation models involves three steps: building hierarchical geometric models based on elementary geometry, associating motion definitions with some elementary geometry and specifying connections to related elementary geometry.

### 4.2.1 Building hierarchical geometric models



The hierarchical geometric modelling includes three steps. Elementary primitives are first defined in their local co-ordinate systems. They are then positioned by specifying geometric constraints with their parent geometry. Finally, they can be translated into desired positions by shipping in their parent co-ordinate systems.

Local co-ordinate systems are defined to be consistent with VRML primitive definitions, since our final simulation models are represented in the VRML format. This makes it easier to transfer internal model definitions to a VRML file. The primitive definitions in their local co-ordinate systems are shown in Fig. 4. The origins are in the centres of primitives. Primitives: cones and truncated cones are defined in a similar way. Based on a local co-ordinate system, an imaginary bounding box can be attached to each primitive. Its six faces are used as constraint planes. The faces perpendicular to X-axis are called the right (on the right hand side) and the left (on the left hand side) faces. In a similar way, the faces perpendicular to Y-axis are called the top and the bottom faces. The faces associated with Z axis are named as the front and the back faces.

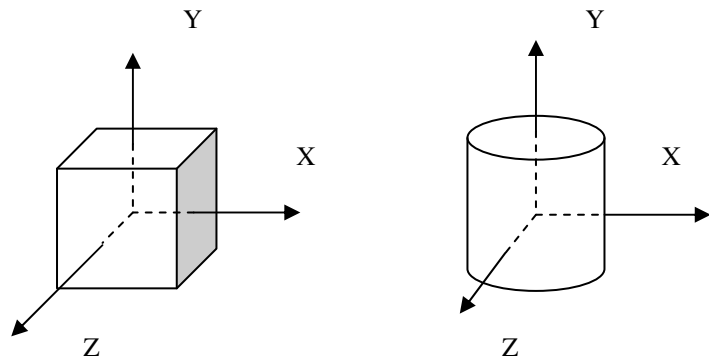


Fig. 4. Primitive definition

In order to create module geometry, designers can interactively specify the sizes of the primitive and position it. As an example, a box feature can be specified with sizes along three dimensions in terms of length, depth and height. For the first geometry, it is located at the origin of the default module co-ordinate system. Meanwhile, in the modelling tree window, the system

will set up a “Root Node” as the root of the modelling tree and link the first geometry as its first child node. In Fig 3, the first geometry (box) is linked to its parent (the root). After receiving the first geometry, the designers need to select a parent node and then create its child node. Once a parent node has been selected, the following nodes will become its children until a new parent node is chosen. For a child primitive, if it is not directly linked to the root node, the designers can input its sizes and specify a constraint by indicating its position relationships with its parent bounding box in terms of attaching on the right or left faces, on the top or under the bottom, and on the front and back faces. From this constraint, the system can determine transformation parameters and attach the child geometry onto the centre of a specified face. For example, a cylinder (Fig. 3) is attached on the top face of the box and located in the centre. The system uses the centre of a constraint face as a default position, because the majority of assembly constraints have central alignment relationships. Of course, child geometry can be edited into any position in its parent co-ordinate system. To do so, a child node needs to be first selected and then the system will display its parent co-ordinate system using three axis lines as in Fig. 3. With references to the parent co-ordinate system, transformation parameters can be easily specified. Finally, the system will update models. In this way, designers can easily build up a module model with desired structures and geometry. Models can be displayed in the Java3D window with interactive visualisation controls of dolly, tracking and tumbling. Using Java3D, these controls are much easier to implement. The models can also be viewed as surface models in the Java2D graphics window.

#### **4.2.2 Defining motions**

Based on a geometric model and its hierarchical tree, designers can interactively define motions associated with the corresponding elementary geometry (parts). The motions can be divided into general motions and state motions. The general motions can be described by position translations or rotations. They are driven by actuators, e.g. motors. The state motions can be

described by colour changes, which are driven by sensors to indicate the sensors' state. The motions can be specified by keyframe values of positions or colours, which correspond to the cycle time intervals. If a motion is directly driven by an actuator or a sensor, the motion is called an activated motion. If a motion is driven by an activated motion under a certain mechanism, the motion is called inactivated motion. An activated motion can be mapping to a control component, whereas an inactivated motion can not be linked to a control component. For example, a feeding module (Fig. 5) is created with this tool. On its tree, node names can be changed from primitive names to feature names. The two cylinder guides: *guide1* and *guide2* are children of the base part. Colour changes of the *guide1* might correspond to a sensor's state changes. For instance, while the sensor is on, the *slide-x* might move. To specify this state motion, the *guide1* node on the tree should be selected. The motion specifications can then be filled up in a pop-up window shown in Fig. 6. In the window, a component name is first specified, e.g., "guide1-sensor". Through this name, the motion is linked to a control component later. Following this input, the time intervals are entered. The first interval is assigned as 0; it corresponds to an initial state. The second time interval (50 seconds) indicates how long the second state will last. Finally, the corresponding colours in R, G, B three components are specified as key frame colour values. The colour changes of the *guide2* might be consistent with the changes of the *guide1* to respond to the same sensor. Thus the motion of the *guide2* could be an inactivated one, which might be driven by the component *guide1-sensor* and specified in the "Driven by" input field. For an inactivated motion, there is no need to give a component name. The general motion of the *slide-x* can be specified in a similar way. The corresponding position changes will be filled in the related dialogue boxes.

After specifying various motions, the system would produce the corresponding control scripts and routes for VRML simulation.

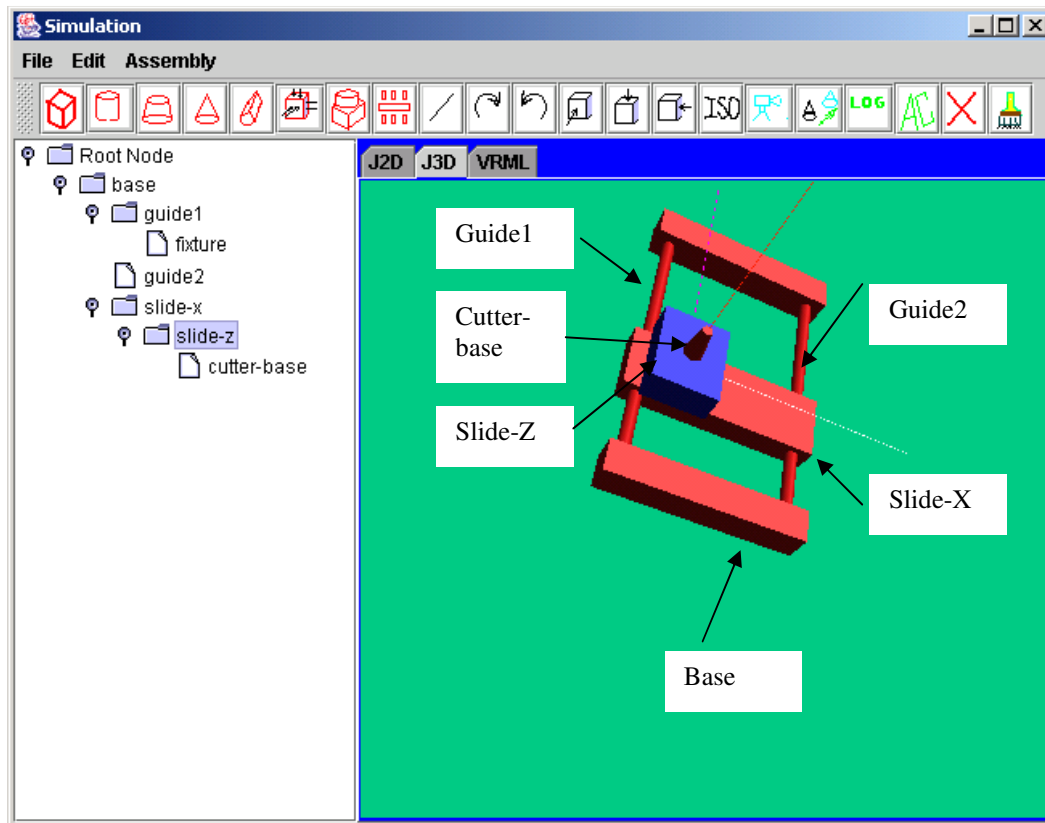


Fig.5. Motion definition

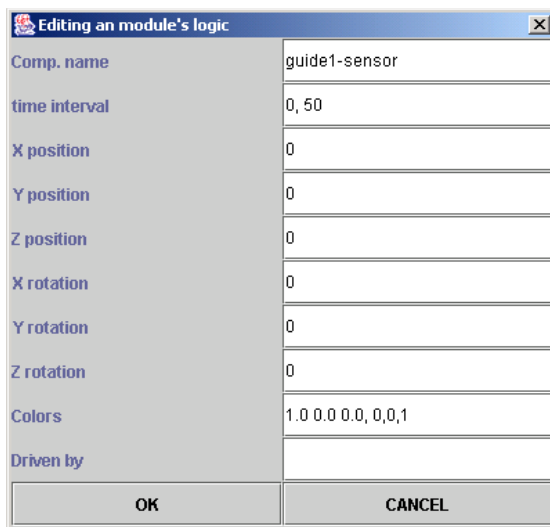
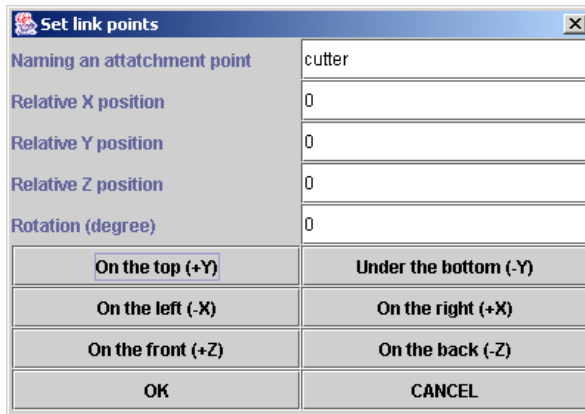


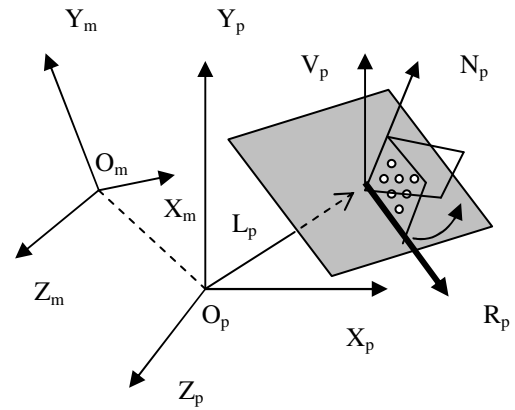
Fig 6. Motion specifications

### 4.2.3 Specifying connections

Within a distributed manufacturing environment, module suppliers are likely to be globally distributed. In a most possible scenario, a module manufacturer would provide connection (assembly) information to his relevant manufacturing partners. Therefore, assembly relations between modules, such as mating conditions, should be negotiated prior to design and manufacturing a module. The assembly relationships can be pre-described as a unified interface assembly feature (connection) associated with elementary geometry in modules. Creating an assembly model (machine model) can be done automatically by mapping the unified interface assembly features, rather than by interactively specifying geometric constraints as in any commercial CAD systems. This would allow non-CAD users to model a machine in a higher level. The use of the connection features provides designers with a new paradigm for rapidly creating sub-systems or machines in a ‘drag-and-drop’ manner.



(a) Connect definition



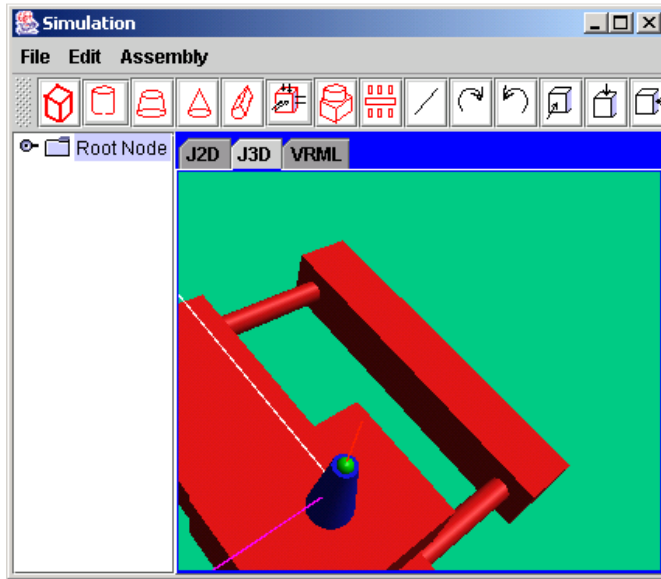
(b) Implicit constraints

Fig. 7 Connection and its constraints

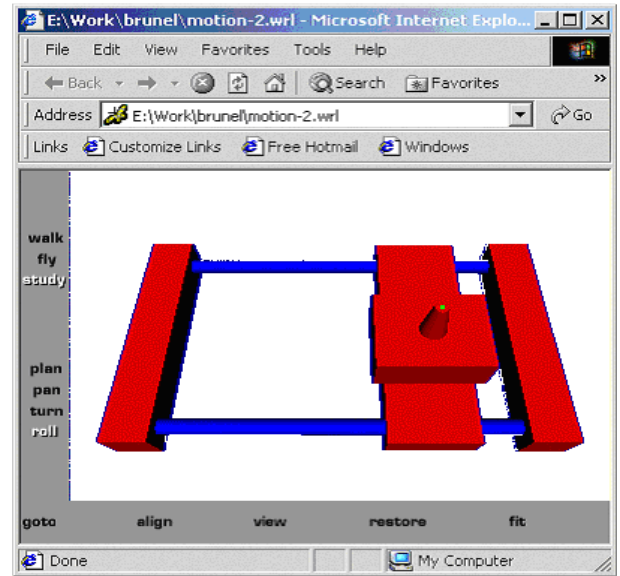
A connection (unified interface assembly feature) in this system is defined as a relatively small sphere on a face of its elementary geometry. In order to define a connection, an

elementary geometry node is first selected, such as “cutter-base” in Fig.6. And then a definition window can be activated (see Fig. 7(a)). In the window, designers can specify the connection’s name, e.g., “cutter”, its locations (on the different attachment faces: the top, the right, etc) and its relative positions to the centre of the attachment face. This information provides the following assembly constraint information: positions, orientations and mating planes. Positions can be described as the vector  $L_p$  in the local primitive co-ordinate system (LCS)  $O_p-X_p-Y_p-Z_p$  (Fig. 7(b)). The normal ( $N_p$ ) of the contacting face will serve as orientations. Based on the normal vector  $N_p$  and a unit vector  $V_p$  parallel to the  $Y_p$ , a reference vector  $R_p$  can be obtained by finding the cross product of vectors  $N_p$  and  $V_p$ . Then a reference plane is defined by the vector  $N_p$  and  $R_p$ . Another orientation parameter can then be defined by specifying a rotation angle  $\beta$  of the reference plane about the normal vector  $N_p$ . If the vector  $N_p$  is parallel to the vector  $V_p$ , the vector  $R_p$  will then be assigned as a unit vector parallel to the  $Z_p$  axis. In this way, three assembly constraints are specified implicitly by mating positions, mating attachment faces and mating reference planes. The local definitions:  $L_p$ ,  $N_p$  and  $R_p$  can be transferred into the corresponding module’s co-ordinate system (MCS)  $O_m-X_m-Y_m-Z_m$ . As a result, the corresponding definitions:  $L_m$ ,  $N_m$ , and  $R_m$  can be obtained. The connection feature is displayed as a small sphere on the specified attachment face.

After specifying a module’s hierarchical geometry, motions, and connection features, the final module definition can be displayed in the Java3D window (Fig. 8 (a)) and saved as the native format in Java3D and as VRML format. The module can be checked over the Internet as shown in Fig 8(b) or tested in the embedded VRML viewer window. If any thing is wrong, modifications can be made easily.



(a) Interface geometry



(b) VRML module checking

Fig. 8 Module Display

### 4.3 Defining a sub-system or a machine

Defining a sub-system or a machine can be achieved by assembling modules or sub-systems. A sub-system or a machine is a hierarchical assembly of modules or sub-systems. It has differences from flattened CAD assemblies [19]. An assembly in CAD systems is based on assembly constraints defined in global co-ordinate systems. Thus, assembly sequences are commutable. In hierarchical assembly, every module is a hierarchical assembly of elementary geometry. While assembling, the first module is aligned with the assembly default co-ordinate system; another module may be loaded afterwards. The system will then search for relevant connections by matching their names and solve the corresponding implicit assembly constraints between a connection defined under its LCS in the current assembly and one defined in the MCS associated with the next-module. The transformations will be automatically computed and the next module will be treated as a child of the corresponding elementary geometry in its parent module. In other word, hierarchical assembly is based on the transformation between a local co-

ordinate system (LCS) and a global co-ordinate system (MCS). This is the reason for that a connection must be defined in both its MCS and LCS. Assembly sequences are incommutable.

In this system, there are two ways of conducting assembly. One is based on modelling trees (Fig. 2c). The system will automatically search a tree, match connections between a parent module and a child module and assemble them hierarchically as shown the above. The other is direct assembly based on modules defined in their VRML files. The next section will give more details.

#### **4.4 The VRML-based assembly**

In a distributed engineering environment, modules in VRML files can support new applications like design repository [20]. A module can be visualised and simulated over the Internet. With this assembly tool, modules can also be easily assembled together into a sub-system or a machine. Designers can assemble modules in a “drag-and-drop” way, avoiding to selecting various low-level geometric elements, e.g., faces and edges, to specify assembly constraints as in most commercial CAD systems.

In order to assembly VRML modules easily, we first analysed the VRML file structure and developed an extended VRML format for containing our connections (unified interface assembly features).

The extended VRML format contains an connection geometry description and its constraints information group. The connection geometry (a sphere) description is defined as a child node of its parent node in a VRML file. The constraint information group is represented as a commentary group of VRML comment lines as shown below. It starts with the line “#Interface-assembly-info” and ended with the line “#Interface-assembly-info-end”. In the body of this group, each connection assembly feature is described in a sub-group of three lines. The first line indicates the feature’s name. The second line contains assembly information in terms of local positions ( $L_{p,x}$ ,  $L_{p,y}$  and  $L_{p,z}$ ), normal directions ( $N_{p,x}$ ,  $N_{p,y}$  and  $N_{p,z}$ ), and relative rotation  $\beta$  about



the local normal; and the global positions and normal directions. The third line ends this subgroup. If a module has more connection features, there will be more group information in the body.

```
#Interface-assembly-info
#Linkpoint Name
#Linkpoint_info  $L_{p,x}$   $L_{p,y}$   $L_{p,z}$   $N_{p,x}$   $N_{p,y}$   $N_{p,z}$   $\beta$  Global  $L_x$   $L_y$   $L_z$   $N_x$   $N_y$   $N_z$ 
#Endlinkpoint
#...
#Interface-assembly-info-end
```

The connection geometry description is represented as a VRML *transform* node. An example is shown below. It defines a sphere shape on the specified contacting face. The description starts with the feature's name. The *translation* and *rotation* nodes specify the positions of the sphere. The internal *rotation* node is used for holding information about relative rotation about the local normal. The *shape* node can be substituted by a module.

```
#Link_test
Transform {
  translation 50.0 0.0 0.0
  rotation 0 0 1 0
  children [
    Transform {
      rotation 1.0 0.0 0.0 0.0
      children [
        Shape {
          appearance Appearance {... }
          geometry Sphere { 2 }
        }
      ]
    }
  ]
}
```

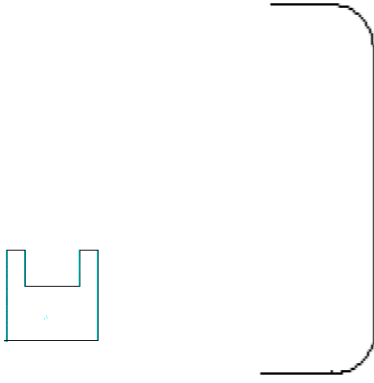
When assembling two modules in VRML files, the first file will be parsed to find the local assembly information from commentary groups for connections. The second file will also be parsed to find the global assembly information for connections. The system will then match two connections and compute transformations. Afterwards, the system will create a sub-system file by loading the first file in and changing the parameters in *translation* and *rotation* nodes within the

matched connection geometry based on the corresponding assembly transformations and inserting related contents from the second file into the *shape* node. Meanwhile, the global assembly information from the second file will be modified under the sub-system co-ordinate system. In this way, two sub-systems or modules can be assembled together easily.

#### **4.5 Creating general extrusions**

The use of various primitives may have some limitations on creating more complex geometric models. In order to make geometric simulations to have more real appearances, the system provides a tool to create general extrusions.

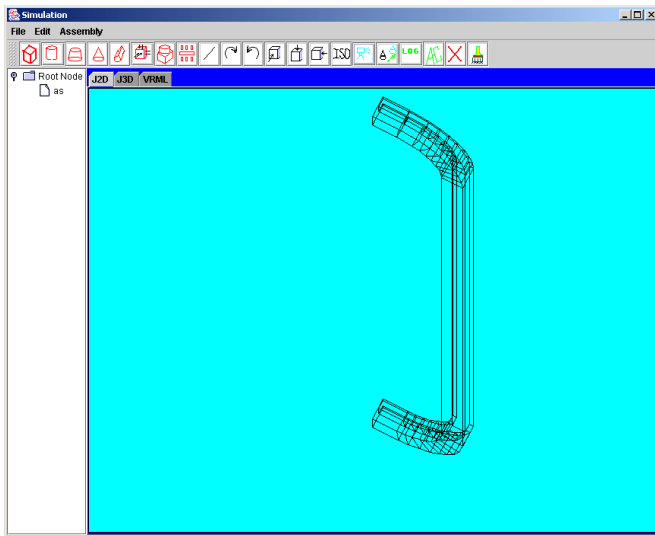
A general extrusion can be defined by a 2D cross section travelling along a 3D path. In the VRML 2.0, a cross section of an extrusion is described in the X-Z co-ordinate plane. In order to keep consistent with the VRML 2.0 and simplify definitions of extrusions, a general extrusion in this system is defined by a 2D cross section in the X-Z plane and a 2D path in the X-Y plane. 2D cross sections and paths can be either described interactively by entering a sequence of line segments and arcs or inputting from DXF exchange files from commercial CAD packages. Internally, cross sections and paths are represented as successive straight-line segments. After obtaining a 2D cross section, e.g., one in Fig 9 (a) and a 2D path, e.g., one in Fig 9 (b), the corresponding extrusion can be obtained and displayed in the java2D window (Fig 9 (c)) and in the Java3D window (Fig 9 (d)). In the java2D window, designers can interactively specify connections on selected facets. The extrusion can then be outputted as a special module and can be assembled with another module or sub-system.



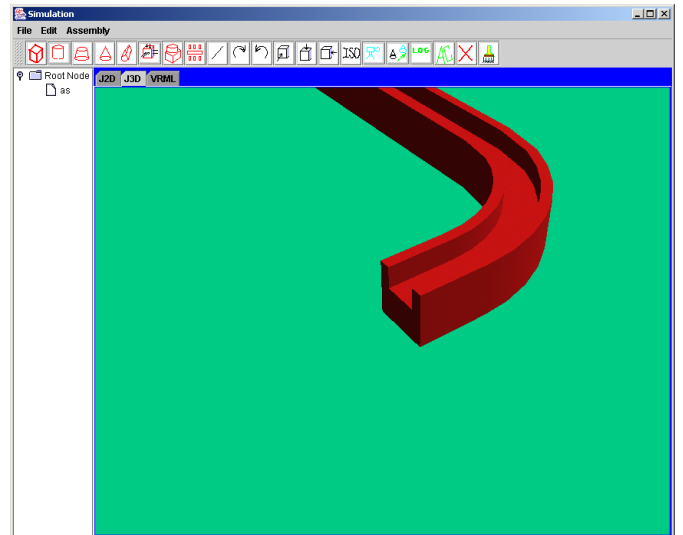
(a) Cross section



(b) Extrusion path section



(c) Surface model



(d) Shaded model

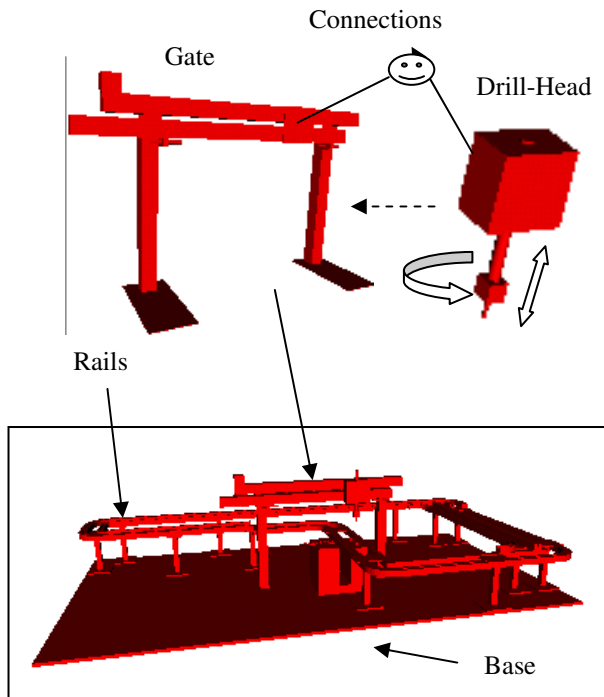
Fig. 9 General extrusions

#### 4.6 Integrating with CAD models

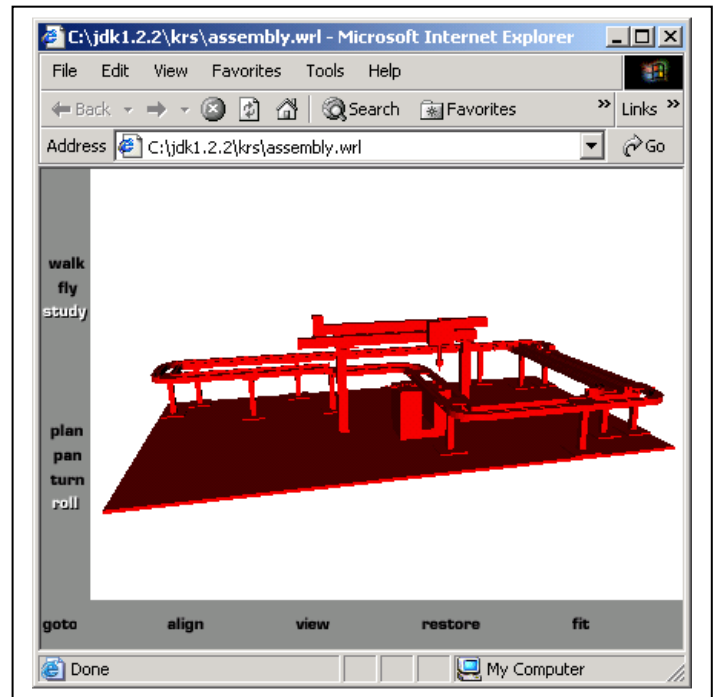
Apart from the creation of general extrusions, this system can integrate CAD models into its modelling. Various CAD packages can be used for modelling a variety of complex parts and output models into VRML files. Based on the CAD models, it is easy to find out information about connection features in terms of positions and orientations. Afterwards, the VRML files of the parts can be interactively edited to add connection features and then saved as special modules like general extrusions. In this way, it is easy to include more complex parts' models into

simulation modelling. Integration of CAD packages can support different levels of details (LODs) in the simulation models.

## 5. Case study



(a) Assembly process



(b) Assembly simulation

Fig. 10 Case study

A case study illustrates the simulation modelling techniques applied in a manufacturing station (Fig. 10). The station includes the following modules: the Base with fixtures, the Rails, the Gate and the Drill-Head. The Rails is created by general extrusion (Fig. 9), and assembled to the Base through fixtures. The Gate module is created from the system and it has a plate on the horizontal frame. The plate geometry has a motion along the frame and a connection with respect to the Drill-Head module. On one feet of the Gate, there is another connection to the Base. The Drill-Head module has a corresponding connection to the Gate module. It also contains rotation and translation motions (Fig. 10 (a)), which can be checked in the VRML browser window. The Gate is a child of Base and the Drill-Head is a child of the Gate. During the assembly process, at any

point, sub-systems can be tested. After finishing the assembly, the machine can be animated as shown in Fig. 10 (b) to check its functions and design. Finally, the machine simulation model can be linked to a real distributed manufacturing system via the VRML EAI interface to emulate the system as shown in Fig. 1.

## **6. Conclusion**

The new 3D simulation modelling approach can support our distributed machine design and control paradigm with respect to simulation and emulation of machine behaviour. Modules can be rapidly modelled through primitives. Complex modules can be obtained by combining general extrusions or integrating CAD models. The use of the connection features and the extended VRML format makes the creation of sub-systems or machines quite simple. Designers can visualise and animate modules in VRML browsers for checking and simply assemble modules in a ‘drag-and-drop’ manner. This makes the component-based machine design more re-configurable and flexible.

The current tool is a Java application and is easily to be converted into a Java Applet for Web-based applications. This tool can also be further developed and applied into conceptual design applications by adopting on-line sketching input [21].

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