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A Study on Rapid Prototyping using VRML Model

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ABSTRACT

Internet becomes very common tool for communication and data sharing. Virtual reality(VR) on web browser, and virtual prototyping and virtual manufacturing is widely used in many engineering fields. The reduction of overall development process and error minimization during data conversion becomes very crucial where sharing data via Internet and VR. This paper deals with the advantage and disadvantage of VRML format used in RP(Rapid Prototyping), and a software for RP data preparation is developed. If VRML format as an international standard for VR, is replaced with STL format, the weak points of STL format can be overcome and the technique related to virtual prototyping and virtual manufacturing can be addressed more systematically by sharing the data. The system developed in this work shows a good window to get access to a more realistic observation of an object for an RP system from a long remote sites in a more systematic way.

Keywords: Rapid Prototyping, Virtual Reality, Data Conversion, Internet, Data Sharing, STL, VRML

1. Introduction

The needs for Rapid Product Development(RPD) are growing to deal with the rapid change of market, develop and produce high-quality product. Rapid prototyping, as one of RPD techniques, is used to verify 3 dimensional CAD models, evaluate its functionality, and manufacture tools for test and production.

The technique to reduce the time for development of new products are currently combined with the Internet, and it is realized by fast network speed and Virtual Reality. Man can see, hear and touch in the environment provided by computer with virtual reality. This environment is referred to as Virtual environment or Cyber space, and man can get information by maximum use of sensible organs. 3 dimensional vision is provided to human via virtual reality like the same way as that man see objects through his eye in real world. Man can acknowledge information easily and fast in virtual environment so that virtual reality is applied to various fields, especially in virtual manufacturing, and virtual prototyping are used in the filed of engineering. Virtual manufacturing is still in the process of the simulation and visualization, and is expected to be studied more in the future. In this paper, the solution for rapid and efficient product development is proposed with connection to the RPD and Virtual reality techniques via Web for sharing CAD/CAM information.

1.1 Related works

Many researches on RP have been studied in the field of hardware, software and materials after development of the first commercial RP equipment in 1987, and the precision and economics of the RP equipments have been issued a lot these days. But surface quality of the RP products is not so good without post-process provided, and the precision is not as good as that of machining.

Kevin[1)] proposes the characteristics of a new file format which compensates the weakness of current STL file format. Hae-seong Jee[2] develops a visualizing technology and neutral feature models for 3D printing. Young-ho Chai[3] studies virtual clay modelling and proposes virtual prototyping systems including tactical elements. Tanaka[4] develops a system for verifying part assembly and visualization. But, in the case of parts interference, an algorithm for checking the interfering regions, interfering volume, and shifting shapes without interference is not provided. Sung-soo Kwon[5] develops a simulator for car driving, and Hyoung-joong Kim[6] designs GUI for car navigation system with use of virtual reality. In the case of RP, rapid and efficient communication between a manufacturer and a designer is necessary to solve the problems of 3 dimensional model data generated from different CAD systems. Thus the generation of RP data and sharing techniques are proposed in this paper using WWW and virtual reality.

2. VRML model as input of rapid prototyping

STL file format as a standard input to RP is formed by Albert Consulting Group, which approximates 3 dimensional solid model with triangular facets, and the developers of CAD systems have selected it as standard output. Most commercial CAD systems support STL file format, and some softwares have been developed to convert several standard inputs like IGES, STEP to STL. Previous algorithms for RP are based on the input of STL file.

2.1 Characteristics of STL file format

STL file format is composed of a normal vector and three vertices in each triangle. Vertices should be arranged counterclockwise to the direction of normal vector following Right Hand Rule, and Vertex to Vertex Rule should be satisfied which means a vertex in a triangle should be the vertex of all the adjacent triangles [7].

ASCII and BINARY format are used in STL file, and BINARY format is generally preferred because its size is approximately a quarter of ASCII format. BINARY file describes the name, the number of all triangles, three vertices and normal vector of all triangle counterclockwise.

The profit of STL file format is to translate data easily between different CAD/CAM systems. That is to say, STL file can be easily obtained to other CAD/CAM systems if a model is divided by triangular mesh, and any additional information is unnecessary. But many modelling data are composed of surfaces, and the translation of the surfaces to the triangular mesh is impossible without errors.

The con of STL file is that it needs big storage due to the repetition of vertex and does not have topological data because it converts CAD model into many triangles within tolerances. Consequentially, data translation gets slow and complicated if STL file is inputted.

In the case that the model is composed of many surfaces, numerous triangles are needed, and efficient data transaction gets difficult because STL format does not have topological relation between vertices and facets.

New file formats to substitute STL file are studied by L. E. Roscoe[8], P. Vuyyuru[9], and M. J. Wozny[10] to tackle the problems in STL file format, but they are not used because commercial CAD systems do not support them.

2.2 Virtual reality and VRML

Virtual reality means the virtual world where human can see, touch, smell, hear and taste. The concept is proposed by Jaron Lanier in 1989 for the first time. Virtual reality in mechanical engineering is applied to virtual prototyping and virtual manufacturing.

Gregory Lee[11] defines virtual prototyping as the operation to visualize and test before generating CAD model substantially, and the technique to verify any assumption given to the development of new products. And it can deal with the design change efficiently because it is applied before the prototyping is built. Assembly test and kinematical motion test is done by the virtual reality applied.

Kazuaki Iwata[12] defines virtual manufacturing as the way to use virtual reality to production system by the simulation of manufacturing process and the computer model to produce in lot size.

Due to the development of virtual reality, IVR (Internet Virtual Reality) has been studied which enables the internet users to experience 3 dimensional virtual reality to without any additional hardware systems. Virtual reality spreads rapidly with the browser for virtual reality using web. This means that virtual prototyping and virtual manufacturing can be used anywhere only if internet and web browser are provided. CAD models are visualized without any CAD system or viewer.[13]

VRML(Virtual Reality Modelling Language), which is used for modelling virtual reality, is established with

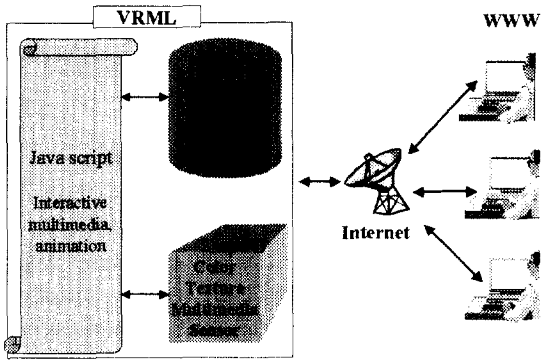


Fig. 1 Sharing VRML via WWW

specification 1.0 by Anthony Parisi, Gavin Bell, Mark Pesce.

VRML is currently adapted as international standard (ISO/IEC 14772-1), and it is in the basis of the Open Inventor and spreads to global world via WWW with the development of OVLib, fast VRML analyser. It can define an object which allows interactive action with multimedia and can be programmed by JavaScript.

Nodes, the definition of an object, are arranged in hierarchical structure which is called as Scene Graph, and they are distinguished from others and make an effect on others. Nodes have fields to represent their property, their own name, and hierarchical child or parent node. Child node inherits all the properties of its parent, which makes VRML called as object-oriented language.

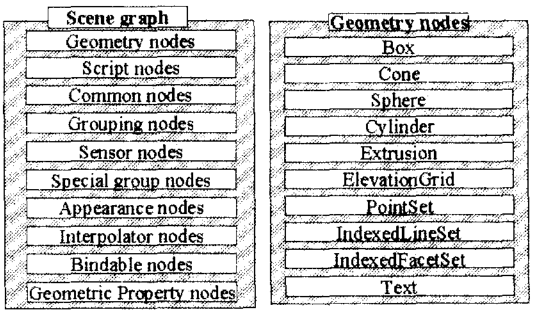


Fig. 2 Nodes of VRML and Geometry nodes

3. Rapid prototyping using VRML

3.1 Advantage

If VRML file is used in RP, its own advantage can be utilized while geometric error is not added in the comparison of STL input. Substantial advantages are as follows:

1. Models are visualized through web browser, and the model data are shared on WWW without any data manipulation.
2. Model data are shared with the related techniques such as virtual reality, virtual prototyping, and virtual manufacturing.
3. Sales to the virtual market are prepared with the same data using interactive action with multimedia.
4. More than 90 % of real models are composed of CSG elements, and they can be used directively in RP.
5. Model, support structure and their slices are visualized through virtual reality. If there are errors in CAD models, the errors can be solved though communication on the web.
6. Processes are implemented fast due to the produced file size because vertices data are not repeated as in STL.
7. Topology between triangles or edges is easily detected through vertex index.
8. Algorithms for RP are used without modification.
9. Errors do not happen during translation from VRML to STL and vice versa so that those two are compatible.

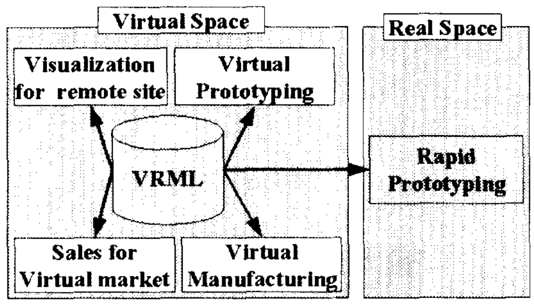


Fig. 3 Usage of VRML on prototyping process

3.2 Compatibility with STL file

IndexFaceSet node in STL and VRML are compatible. IndexedFaceSet arranges all vertices and normal vectors on coord field and normal field without overlapping. Vertices to compose each surface are recorded with following constant direction in CoordIndex field, while normal vectors are recorded following surface sequence in normalIndex field, so that the same data are stored as the STL file format. VRML represents not only triangular facet but also polygonal facet, color, texture and event which allows interactive action with users.

Table 1. IndexedFaceSet

```
IndexedFaceSet {  exposedField SFNode color NULL
 exposedField SFNode coord NULL
 exposedField SFNode normal NULL
 exposedField SFNode texCoord NULL
 field SFBool ccw TRUE
 field MFInt32 colorIndex [] # [-1,∞ )
 field SFBool colorPerVertex TRUE
 field SFBool convex TRUE
 field MFInt32 coordIndex [] # [-1,∞ )
 field SFFloat creaseAngle 0 # [0,∞ )
 field MFInt32 normalIndex [] # [-1,∞ )
 field SFBool normalPerVertex TRUE
 field SFBool solid TRUE
 field MFInt32 texCoordIndex [] # [-1,∞ )
 eventIn MFInt32 set_colorIndex
 eventIn MFInt32 set_coordIndex
 eventIn MFInt32 set_normalIndex
 eventIn MFInt32 set_texCoordIndex
}
```

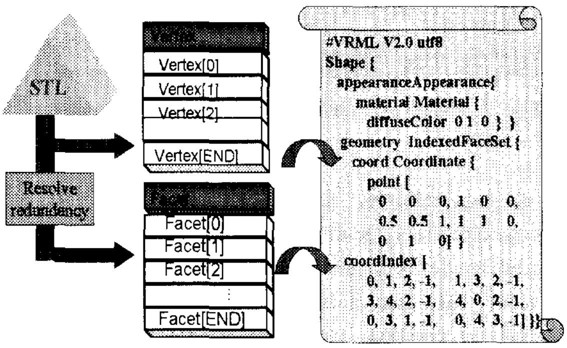


Fig. 4 STL to VRML translation

STL file format represents only geometry data, so VRML and STL are translated into each other without errors. But, if IndexedFaceSet is used, file size becomes small because the definition of vertices and normal vector is not repeated.

3.3 Data structure for rapid prototyping

Extrusion, ElevationGrid node and CSG element in VRML are stored in the same way as IndexedFaceSet by dividing a model into triangles within tolerance. This means RP algorithm based on STL file is applied directly, and, in special cases, geometric data can be obtained using CSG element within tolerance.

Fig. 5 shows the Scene which represents all scenes in VRML and the data structure to store an object.

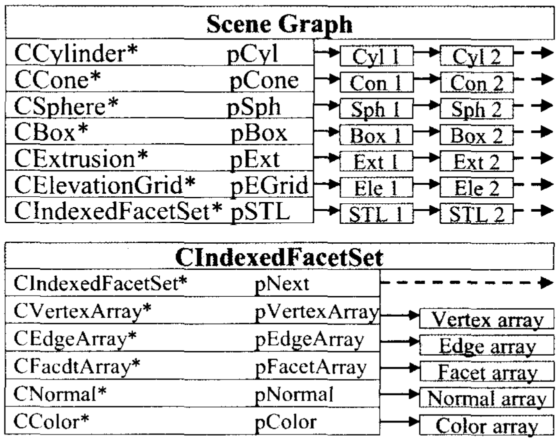


Fig. 5 Data structure for VRML

3.4 Reconstruction of topological relation

There is a need for reconstructing topological relation on facet and edge for rapid and efficient CAD data transaction. Reconstructed topological relation simplifies the algorithms for the orientation decision, automatic generation of support structure, and slicing. Each vertex, edge, facet and normal vector are added and removed by allowing pointer to define dynamic array. And, by allowing random access to all geometric elements, more efficiency can be obtained if compared to a linked list which needs sequential access. VRML inherits all definitions such as coordinate transformation and color from a parent object to a child object, and all properties should be adopted to each objects inherited. An algorithm which reconstructs the basic data in Fig. 6 in array is shown in Fig. 7 and its overall steps are as follows.

CIndexList	
int	nIndex
CIndexList*	pNext

CPoint	
float	x
float	y
float	z

CNormal	
float	x
float	y
float	z

CVertex	
Cpoint	vertex
BOOL	bIsSharp
CIndexList*	pEdge
CIndexList*	pFacet
int	nTemp

CEdge	
int	nUpperVertex
int	nLowerVertex
int	nNeighborFacet[2]
Bool	bIsSharp
int	nTemp

CFacet	
int	nVertexIndex[3]
int	nNeighborFacet[3]
int	nNeighborEdge[3]
int	nNormalIndex
Bool	bNeedSupport
int	nTemp

Fig. 6 Data structure for IndexedFacetSet

step 1) Read vertex coordinates from VRML and store them in Vertex array.

Step 2) Read facet data from VRML, and triangulate them. Store the vertex index in Facet array counterclockwise, while triangle index is assigned to pFacet in each vertex.

step 3) Store vertex index to nTemp in Vertex array. Vertices in Vertex array are sorted in increasing order based on the build direction on Z-axis.

step 4) The vertices are removed which are overlapped three or more times during the sort. The facet index of pFacet list of a vertex to be removed should be linked to the pFacet list of a vertex to be remained. To classify a vertex index to be removed or remained, the vertex indices to be removed are changed to (-) sign.

step 5) If all the overlapped vertices are removed, the vertex index stored in Facet array is changed to (+) sign.

step 6) Compute a unit normal vector of all facets and store it to Normal array.

step 7) Sort Normal array in increasing order based on build direction of Z-axis and remove the normal vector overlapped. Update the normal vector index of all facets.

step 8) Store 3 edges of all facets to Edge array,. For the next efficient searching, store a vertex which has the larger value in Z-axis to nUpperVertex and a vertex which has the smaller value in Z-axis to nLowerVertex. Store the facet index to nNeighborFacet[0] in Edge array.

step 9) Sort all edges in decreasing order based on the value of Z-axis in nLowerVertex. All edges are dual, and each edge of dual edges is included in different triangle. And the facet index in nNeighborFacet[0] is moved to nNeighborFacet[1] of the other edge, and the edge overlapped is removed. If the dual edges are not composed of two edges, it means there is a hole or overlapping error in CAD data. Update the index stored in pEdge on Vertex array.

step 10) To store the adjacent edge index to nNeighborEdge in a triangle, get triangle data stored in nNeighborFacet of each edge. Store the corresponding edge index to nNeighborEdge of the triangle.

step 11) 3 vertices v1, v2, v3, the ones of facet fn, and 3 facets, Sf1, Sf2, Sf3, the ones with these vertices, are computed intuitively from the data structure. 3 triangles fn1, fn2, fn3 which share an edge with fn, are obtained by expression (1) and store them to nNearFacet in Facet array.

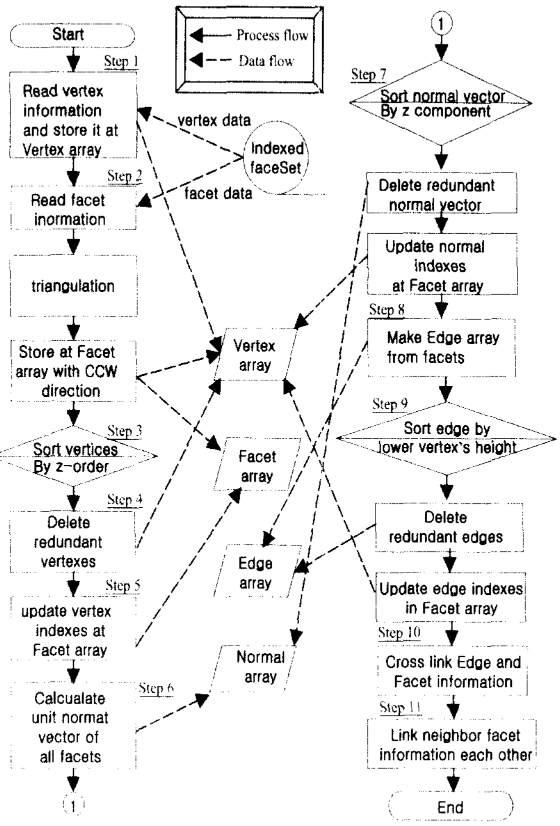


Fig. 7 Flow chart for building data structure

$$f_n = S_{f1} \cap S_{f2} \cap S_{f3}$$

$$\{f_{n1}, f_{n2}, f_{n3}\} = (S_{f1} \cap S_{f2}) \cup (S_{f2} \cap S_{f3}) \cup (S_{f3} \cap S_{f1}) - \{f_n\} \quad (1)$$

With use of the data structure mentioned above, the data on facet, edge, vertex are obtained, and the next operations such as the orientation, support structure, and slicing are processed efficiently.

3.5 Verification of reconstructed data

There can be some errors in STL of VRML file which are converted from commercial CAD systems. The operations such as the orientation, support structure, and slicing can not be processed properly if errors are included in STL file. Most errors in STL file are the hole error where some adjacent triangles do not exist, the overlapping error where more than 3 triangles are overlapped in one edge, and the normal vector error where the direction of normal vector is reversed. The hole and overlapping errors are detected by checking the data structure. If only one triangle shares only one edge, less than two triangles are adjacent to one triangle, or less than two facets share one vertex, then there is hole error in STL file.

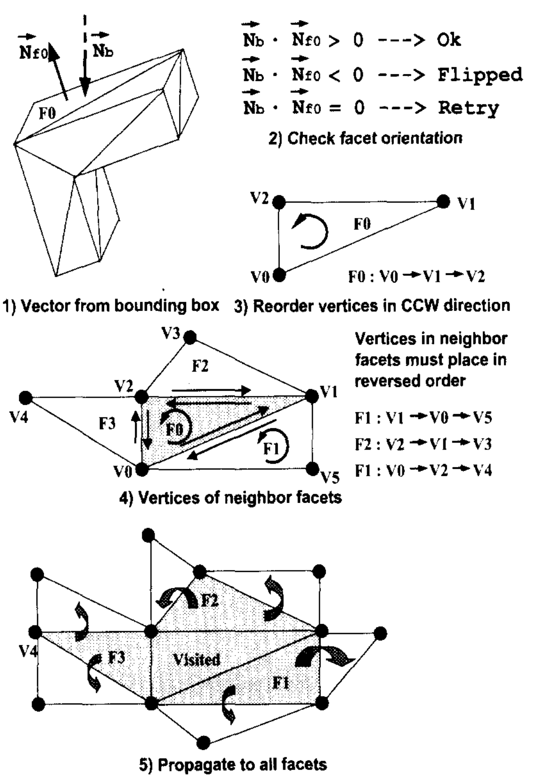


Fig. 8 Normal vector correction for a solid object

If one edge is shared by more than three facets or one triangle is adjacent to more than four triangles, then there is an overlapped error.

Fig. 8 shows an algorithm which corrects the direction of normal vector. Considering the fact that the sequence of vertices shared are reversed if vertices of two adjacent facets are arranged counterclockwise, the direction of all triangles are corrected by computing the direction of one triangle. Considering the direction of vector, Nb, from somewhere far away to an object, dot product of the Nb and the Nf0, which Nb collides with for the first time, should have (+) sign, if the object is solid. If the inner product has (-) sign, the normal vector is reversed. If the inner product is 0, the end point of Nb moves a little and the inner product is computed).

$$\overrightarrow{N_b} \cdot \overrightarrow{N_{f0}} \geq 0 \qquad (2)$$

All normal vectors in one object can be corrected if normal vectors of 3 adjacent facets of the base facet are corrected and other adjacent facets are corrected sequentially. If facets which are not checked exist after the end of correction, it means there are more than 2 objects exist and the objects are divided and corrected.

3.6 Union operation of an object

VRML supports multiple objects, but does not support Union operation between objects. Union operation between the objects interfered makes them one independent object and it can be used in RP. The bounding box of each object is computed and, if the interference between objects exists, then the interference between real objects is computed and the objects are combined into one object.

(step 1) Compute the intersecting lines between two objects by considering the triangles included in intersecting region of bounding box. If the triangles intersect at a point, then skip them. If they intersect on surface, triangulate them with removing intersecting regions and find the intersecting line. If the intersection between all triangles does not happen, it means two objects are totally separated or included. To decide this case, different group ID is assigned to each object and step 5 is implemented.

If all intersecting lines are found, an intersecting loop is formed by connecting all the end points. If the loop is opened, hole errors exist. If many intersecting loops are formed, it means the intersection happens many times.

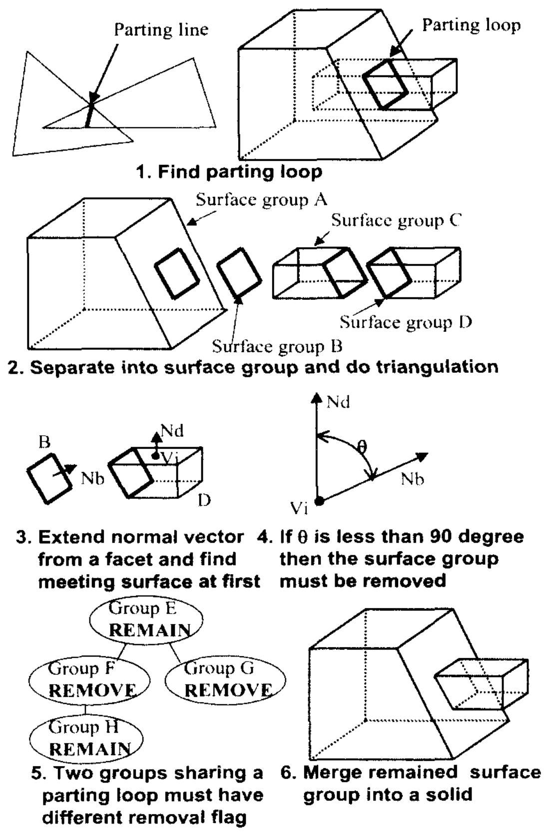


Fig. 9 Illustrative example of Union operation

(step 2) A triangle with intersection is divided into two polygons whose edges are intersecting lines. Those polygons are triangulated, and previous facet data are removed. Different group ID is assigned to the facets in each object.

(step 3) Decide which surface group is removed in an object. Select a triangle and extend the normal vector from its center to a triangle of other object. If the joining angle is 90 degree, the extension of normal vector intersects the edge of 2 triangles. So, compute the normal vector whose joining angle is not 90 degree.

(step 4) Compute the joining angle between two vectors. If the joining angle is less than 90 degree, it is not removed. If the extension of the normal vector does not intersect other surface group, the surface group remain after union operation.

(step 5) Surface group to be removed is decided by the fact that the one of two surface groups with the same intersecting loop should be removed and the other one should not be removed.

(step 6) Remove the triangles which are assigned to be removed, and combine the triangles remained into one object. The algorithm mentioned above is developed to use efficiently the multiple objects in VRML with use of Edge and Facet array based on Vertex array.

4. Experimental result

Software for error verification , support generation, file viewer and converter between STL and VRML is developed with use of Visual C++ 6.0 and OpenGL.

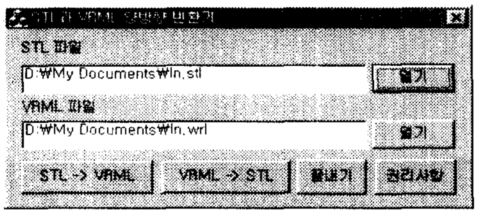


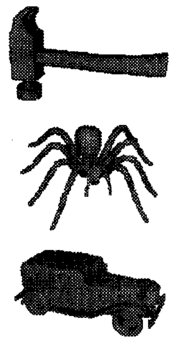
Fig. 10 Dialog box for translator

Software developed makes it possible to share and visualize VRML file, and algorithms for RP can be used directly without any modification. The software corrects errors in IndexFaceSet with direct use of previous module for STL error correction, generates support structure for multiple object in VRML with direct use of previous module for automatic generation of STL support structure. Thus the development of additional algorithm to use the modules for STL is not needed.

Fig. 10 shows the interface for conversion between STL and VRML. This conversion supports STL file of BINARY and ASCII types and VRML 1.0 and VRML 2.0 (VRML 97).

Geometric data are shared and visualized via internet and virtual reality with use of the converter. Fig. 11 shows the result of the models converted. The number of vertices is decreased to the average of 16.8% by removing the vertices overlapped. And the file size compressed is decreased to 43%~76% which is essential for internet connection.

Fig. 12 shows the part for automobiles in VRML and Fig. 13 shows the model converted in STL. Fig. 14 shows a dialog box for error correction, and Fig. 15 shows a dialog box for generating support structure for SLA systems.



Models for testing.

Low data ; STL						
	facet	vertex	uncompressed		compressed	
			ASCII	BINARY	ASCII	BINARY
Hammer	774	2,232	137KByte	37KByte	18KByte	15KByte
Spider	9,286	27,858	1,801KByte	454KByte	243KByte	139KByte
Car	16,646	49,938	3,097KByte	813KByte	402KByte	329KByte

Translated data ; VRML								
	vertex		uncompressed			compressed		
	number	ratio	size	ratio (ASCII)	ratio (BINARY)	size	ratio (ASCII)	ratio (BINARY)
Hammer	377	16.8%	52KByte	38%	140%	9KByte	50%	60%
Spider	4,670	16.7%	637KByte	35%	140%	105KByte	43%	76%
Car	8,477	16.9%	1,148KByte	37%	141%	193KByte	48%	58%

Fig. 11 Conversion benefits.

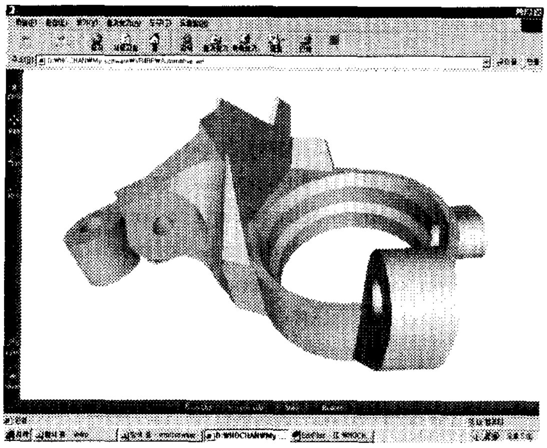


Fig. 12 VRML model of Automotive part

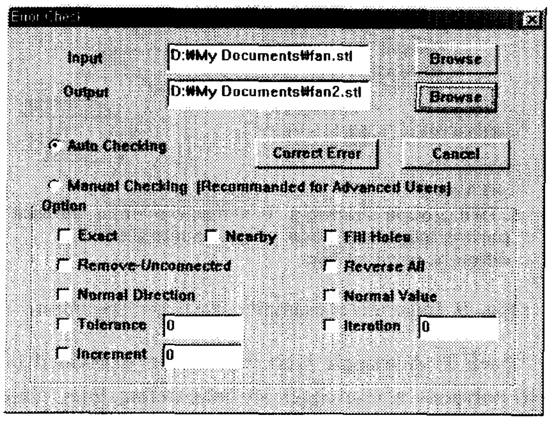


Fig. 14 Error checking and correction dialog

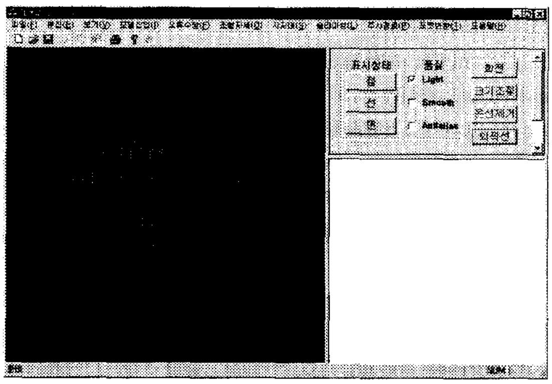


Fig. 13 STL converted model

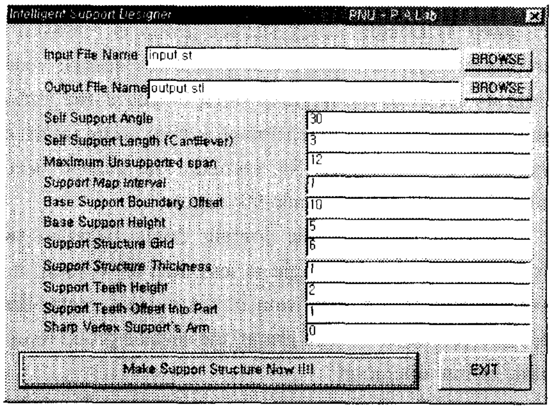


Fig. 15 Support generation dialog

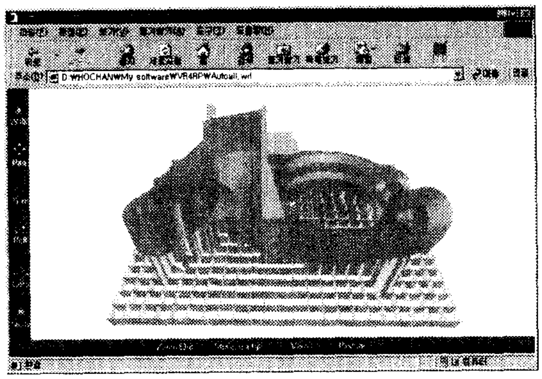


Fig. 16 VRML model with support structure

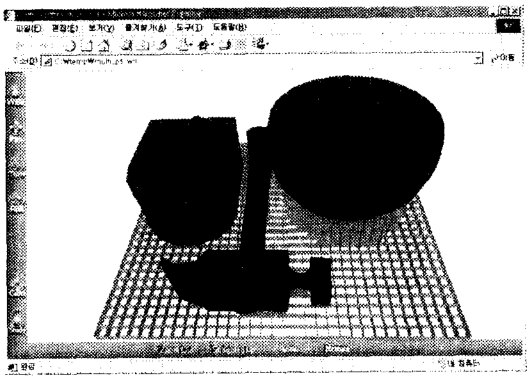


Fig. 17 Multi-object application example

The web browser used is Internet Explorer 5.0 and VRML plug-in is WorldView.

5. Conclusion

Fig. 16 demonstrates the model and support structure can be shared by Web browser via Internet connection. It can be used to a manufacturer and a designer of the model when automatic correction of error is impossible and the discussion on build direction and precision is needed. Fig. 17 demonstrates the models are verified prior to the real build with using the multiple objects, the characteristics of VRML.

This study adopts the data sharing and VRML techniques to RP to minimize the errors during data conversion and total time for development.

It demonstrates that VRML can be used as input to RP and VRML is compatible with STL file format. The advantages are studied when VRML is used and the efficient data structure for RP is proposed. Some necessary points are checked, when VRML is used for RP input, and an algorithm for union operation between objects is proposed. Converter between STL and VRML is developed, and it demonstrates that RP can be implemented with VRML model by using RP algorithm without modification.

Consequentially, if VRML model is used as input of RP, the compatibility with STL format is maintained and efficient processing is obtained by avoiding the problem of vertices overlapped. And visualization and data sharing are possible with WWW and virtual reality. The development of simulator for total build process is proposed for future work.

Acknowledgement

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