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Generic kinematic simulation for verification of laser deposition tool paths

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GENERIC KINEMATIC SIMULATION FOR VERIFICATION OF LASER DEPOSITION TOOL PATHS

By

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This thesis is composed of the following two papers which were reformatted in the style used by the university.

The first paper presented in pages 3-28 titled "GENERIC VISUAL SIMULATION OF MANUFACTURING EQUIPMENT" has been accepted and is in press in the proceedings of the ASME INTERNATIONAL DESIGN ENGINEERING TECHNICAL CONFERENCE (WASHINGTON DC), 2011.

The second paper presented in pages 29-69 titled "GENERIC KINEMATIC SIMULATION FOR VERIFICATION OF LASER METAL DEPOSITION TOOL PATHS" is intended for submission to ASME JOURNAL ON COMPUTING AND INFORMATION SCIENCE IN ENGINEERING.

ABSTRACT

The development of 3D visual simulation tool for machine simulation is a key approach in saving time and reducing cost. It is an important step before a manufacturing operation is performed on a part, as a tool to detect collision and validate the operation results. There are several kinds of manufacturing equipment being used and hence there is a need for the development of a generalized method to visually simulate a variety of machines. This paper presents the research conducted on describing machine configuration in a generic format which not only gives useful information, but can also be used as a tool to generate the parent list and the dependency list, which would aid in the simulation process. This format is also used to describe the type of motion - linear and rotational motion of the machines parts. In this study, a generic movement description file is also presented, which is utilized to compute the machine motion for various axes. This work concentrates on laser deposition in order to demonstrate a manufacturing operation. This 3D simulation tool has been tested on various manufacturing equipment and the results are shown in the paper.

This thesis is composed of two papers. In paper I, a basic version of the algorithm for simulation and generic machine configuration format have been presented. This paper only describes linear motion for machine axes. Paper II discusses in detail about the algorithm, provides results for both translational and rotational motion and enhances the deposition simulation as well as the display scene.

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1. INTRODUCTION

1.1. OBJECTIVE

Simulation of a machine is important before laser metal deposition is performed, in order to check collision detection and validate deposition result. There are several kinds of machines that are used for laser deposition and hence there is a need for a generalized concept for visual simulation of various kinds of machines. This thesis paper presents the research conducted in describing machine configuration in a generic forma and simulating varied mechanisms with that data. This method has been tested to validate deposition results using various examples to demonstrate its robustness and efficiency.

1.2. BACKGROUND

Visual simulation is still very much focused on a single machine or equipment and or is specific to a group of machines. Even though visual simulation of machines is being done since a long time, it has been having a very simple representation of the simulation environment. Also, the solids used in simulation are simple and not sophisticated.

This paper aims to address generic visual simulation of different manufacturing equipment. It consists of a summary on the generic machine configuration representation, derivation of a parent list and a dependency list from it and how this helps in visual simulation of machine movement. This study also specifies the representation of machine motion in a generalized format. In addition, the paper presents some examples of 3D visual simulation of manufacturing equipment and deposition tool paths.

1.3. CONTRIBUTIONS

In the first paper, 3D visual simulation software was developed, that is capable of simulating a tool-path of any machine. The software provides 3D graphical environment to manipulate (translate, rotate, zoom) the tool path. The simulator evaluates a correct position of the tool in space, i.e. the location and the orientation of the tool for an arbitrary sculptured surface. It provides preliminary results that can be used to estimate the errors graphically. [11] It also addresses the issue of visualization of additive manufacturing simulation. It provides a very user friendly approach as the end user has to just write a few text documents based on the instructions specified. Also a generic approach for layer manufacturing has been depicted.

In the second paper, the uniqueness about this tool is that it can be used to kinematically simulate varied serial mechanisms as well as validate varied deposition tool paths for CNC machines. The main aim of the tool is to check errors in the tool paths and to avoid wastage of materials. The difference that underlies this approach is the style in which the machine is being represented in the system. That is, this technique uses a knowledge base of the machine data in order to implement the frame based concept. Machine simulation is used as an approach to validate additive manufacturing tool paths. Integration of this tool with deposition simulation in order to pre-check tool paths with generic approach has been depicted in the paper.

PAPER

I. GENERIC VISUAL SIMULATION OF MANUFACTURING EQUIPMENT

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Abstract

Simulation of a machine is very important before laser metal deposition is performed, as a tool to check collision detection and validate deposition result. There are several kinds of machines that are used for laser deposition and hence there is a need for a generalized concept for visual simulation of various kinds of machines. This paper presents the research conducted on describing each machine configuration in a generic format. A parent - child list and a dependency list obtained from the machine configuration are utilized to form the generic format. Such a format can be used to describe linear and rotational motion of the machines parts. This method has been tested on various examples to demonstrate its robustness and efficiency.

1. INTRODUCTION

Layered Manufacturing (LM) technology, also known as Rapid Prototyping (RP) is a process that involves adding raw material, in layers, to create a solid part directly from a CAD model instead of removing the material as in the case of traditional subtractive manufacturing processes such as machining. LM processes fabricate a physical part in an additive fashion, layer by layer. Metal rapid prototyping is a technique that can produce fully functional parts directly from a CAD. Direct laser deposition is capable to fabricate fully dense metal parts directly from the CAD model. Such a process has drawn interest from aerospace, heavy machinery and other industries. Due to its complexity, this process requires an automatic planning system to drive.

Laser Aided Manufacturing Process (LAMP) lab is using a Fadal 5-axis CNC machine (model VMC3016) as shown in Figure 1, as the motion driver. The deposition nozzle is mounted at the side of the spindle, which forms a hybrid manufacturing system on a single workstation. These are used to restore a damaged part to its original geometry.
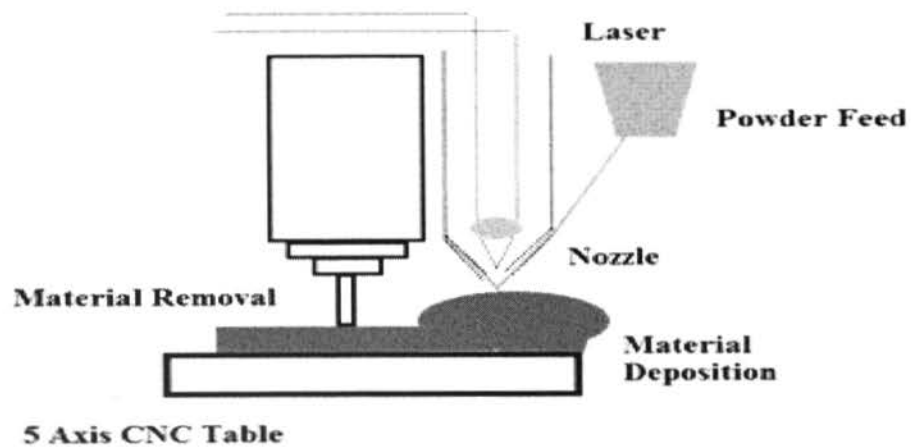
Figure 1. Laser Metal Deposition Process

The final tool path of a machine for laser aided deposition is in the form of G and M codes, which needs to be verified before part repair is performed [12], since the parts are expensive and a small error [1] in the repair action will cost heavy. Thus visual simulation of the entire repair process is done before any practical application of the codes generated. [2 to 8, 14 to 15]

This paper aims to address visual simulation of different manufacturing equipment. The paper will summarize how each machine can be represented in a generic format, derive a parent - child list and a dependency list from it and how this helps in visual simulation of linear and rotational motion. It also puts forth a generalized method for representing tool path data for layer manufacturing. In addition, the paper presents some examples on linear motion simulation using the above format.

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2. RELATED WORK

Defects Visual simulation is still very much focused on a single machine or equipment and or is specific to a group of machines. Even though visual simulation of machines is being done since a long time, it has been having a very simple representation of the simulation environment. Also, the solids used in simulation are simple and not sophisticated. A tridimensional box is used to represent each link with dimensions and positions and the procedure to change the relative position between links in order to correspond to the given trajectory is to transform the tridimensional representation to perspective position to make it look like motion happened. [13]

Following are some other simulation softwares available:

- LINCAGES (Nelson and Erdman 1994), Sphinx (Larochelle et al.1993), SPADES (Larochelle 1998) and Synthetica (Suet al. 2002) : Mechanism design software focus on the dimensional synthesis of planar, spherical or spatial linkages. They do not have interface for constructing mechanisms and simulating their motion.

- WATT by Heron Technologies Inc., SyMech by symech.com and Ch Mechanism Toolkit by SoftIntegration Inc. (Cheng and Trang 2006): These focus on the analysis and synthesis of planar 4-bar, 6-bar or 8-bars. None of them provide a full dynamic simulation for general mechanisms

- Working-Model (Design Simulation Technologies Inc.) and ADAMS (MSC Software Co.): Provide versatile functionalities in modeling and simulating mechanisms. WorkingModel does not support spatial mechanisms, and it does not provide an advanced visualization and interaction functionality. ADAMS does not provide a user-friendly interface.

- MATLAB's SimMechanics: Provides a powerful multi-body dynamics solver. However, its building process is based on block diagram, which is not intuitive (see what is built), and is overly complicated.

- VRJuggler , Vizard Virtual Reality,Virtual Reality Peripheral Network (VRPN), Virtual Assembly Design Environment (VADE), MIVAS:A Multi-modal Immersive Virtual Assembly System, SHARP: a Dual-Handed Haptic Assembly System, Virtual environment for assembly training : However, relatively less work has been done for applying VR techniques in supporting interactive design especially the conceptual design stage.

- Virtual environment (VE): Their focus is not on the construction of mechanical systems but on the dynamic simulation aspect.

- Stan et al. (2008) have developed a VR: for a particular type of parallel robot by using the MATLAB's VR toolbox, which does not provide a 3D stereoscopic immersive visualization.

- VR programs dedicated to the design of spherical mechanisms (Furlong et al. 1999) and spatial mechanisms: The focus of these works is on a particular kind of mechanisms, spherical 4R or spatial 4C, etc., not on providing an intuitive and user-friendly interface for interactively building mechanisms.

- CG VERICUT is dedicated to process planning for machining and only deals with CNC machine simulation. It does not facilitate simulation of additive manufacturing. Another drawback is that it cannot be used to simulate robots or other manufacturing equipment.

3. GENERALIZED SIMULATION OF VARIOUS MACHINES

In Laser deposition for part repair can be done using other manufacturing equipment as well, some of them having more than five axes. Other than laser processing, there are different kinds of additive manufacturing processes like aerosol jetting, electron beam melting that need to be visualized before practically applying them for fabrication of various parts. Thus, there is a requirement for a generalized visual simulation of the different machines, such that the same algorithm can be applied in case of different equipment. Figure 2 shows an overview of how generalized simulation works.

There are three inputs to the algorithm- one is a 3D CAD model of the machine, second is the tool path document and the other is a configuration text file, the details of which would be discussed later in the paper. The flow of data from the configuration text file goes through a series of transformations. The first transformation converts raw data into more usable data lists. The raw data is typically in some domain specific format that is often hard, or impossible, to work with. Data lists are relational depictions of this data.

The raw data is nothing but descriptive information about the machine. From here, the data is transformed into data lists such as parent - child list and dependency list. User interaction controls the parameters of these transformations. The visualizations are all with respect to the application task. Data lists are based on mathematical relationships whereas visual structures are based on graphical properties. Although raw data can be viewed directly, data lists are a vital intermediate step when the data is abstract. The raw data here are the source code, execution data and design documents. This model also points out the need to transform raw data into something more usable [9].

- DELMIA IGRIP focuses on processes like spot welding, painting, arc welding. Siemens Technomatix is a solution to validate and manage detailed product and process data. However, both these applications do not serve their purpose in case of layer manufacturing.

Currently no mechanism design tool simultaneously has the following features:

(1) Visual simulation of additive manufacturing

(2) Providing an intuitive and user-friendly interface

(3) Flexible to support all joint types. [10]

In this paper, a generic method has been developed to represent a machine in the form of numbers and letters in a text document. This could be used for any given machine configuration. Also, a CAD model [16] of the machine can be imported and hence complex structures can be visually simulated. Different kinds of joints are supported as well due to ease of representation.
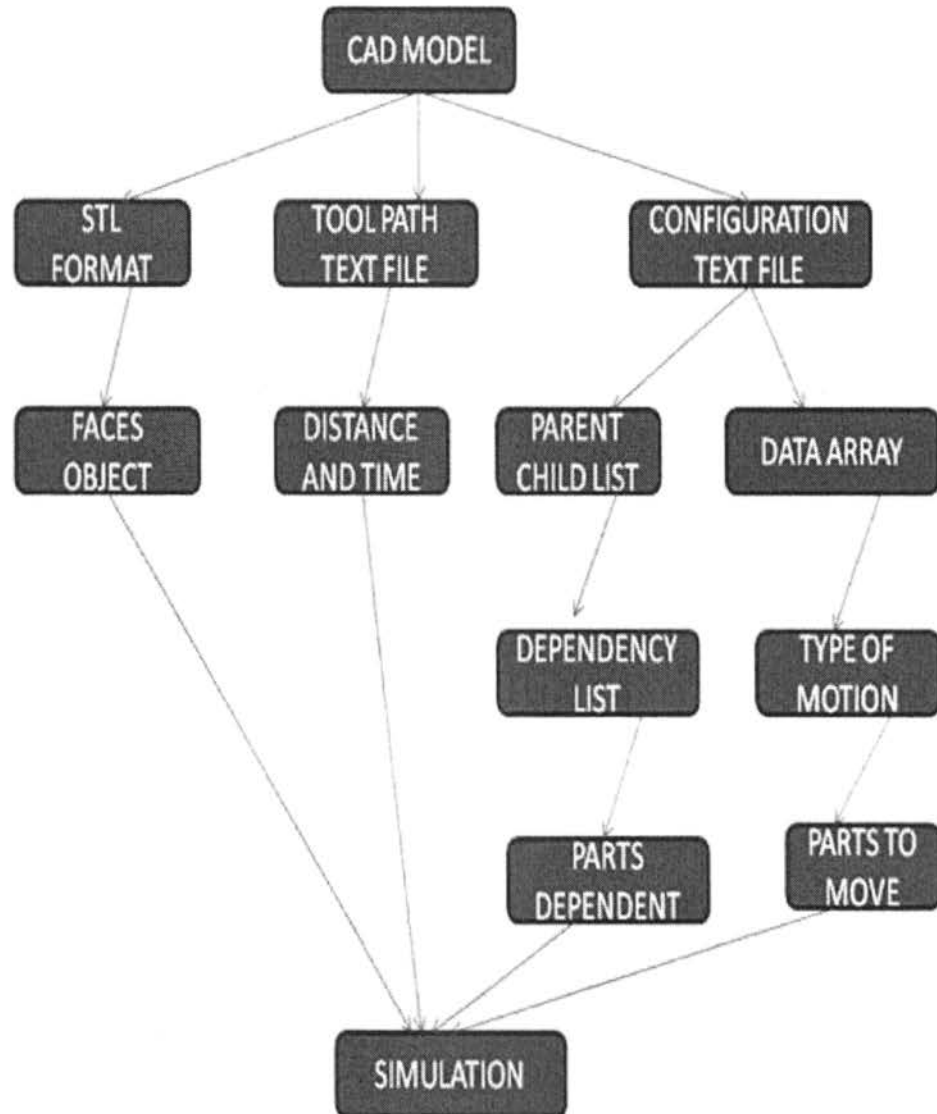
Figure 2. Flow Chart of the Simulation Process

Using the 3D CAD model of equipment as shown in Figure 3, data needed for the configuration file can be obtained as specified. Information from this data can be used to generate a parent - child list and a dependency list, the details of which shall be discussed later in the paper. From the dependency list, the parts to be moved are obtained and also,

the type of motion – linear or rotational is noted. These two are inputs to simulate the machine.

The 3D CAD model as shown in Figure 4 of a machine is converted into stereo lithography (STL) format. This format describes only its surface model, which is widely used for rapid prototyping and computer aided manufacturing. The STL object is transformed into a faces object as shown in Figure 5, which is an array primitive consisting of one sided triangles.

This provides a 3D graphical environment for displaying the visual representation of the machine and the work piece. The 3D n-axis machine model is represented using a faces primitive.

Figure 3. ABB IRB Robot

Figure 4. CAD Model Of ABB IRB Robot

Figure 5. Faces Model of ABB IRB Robot

4. MACHINE CONFIGURATION DATA

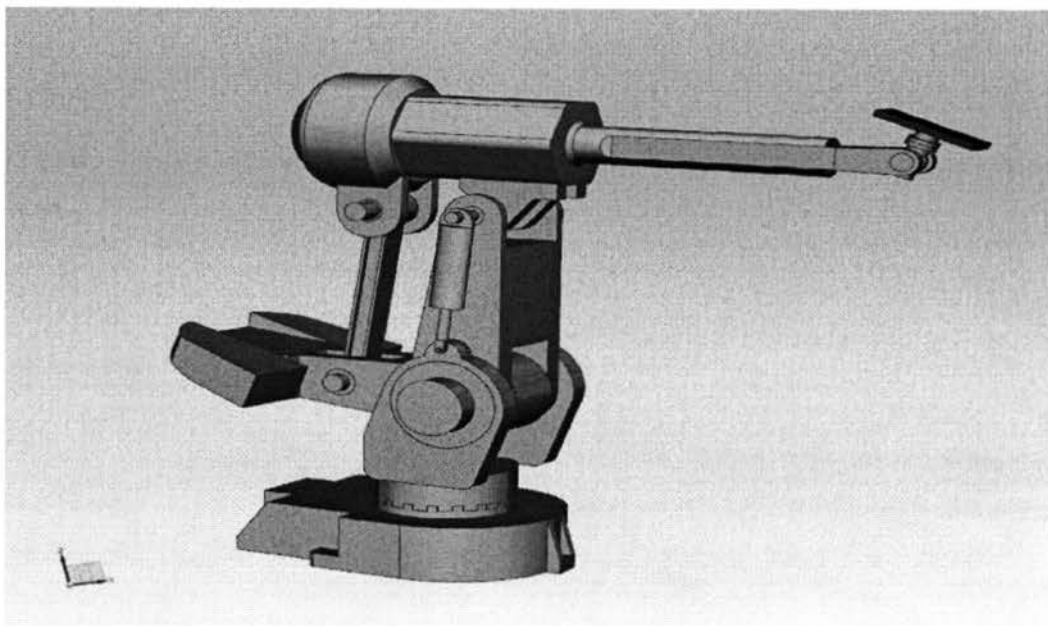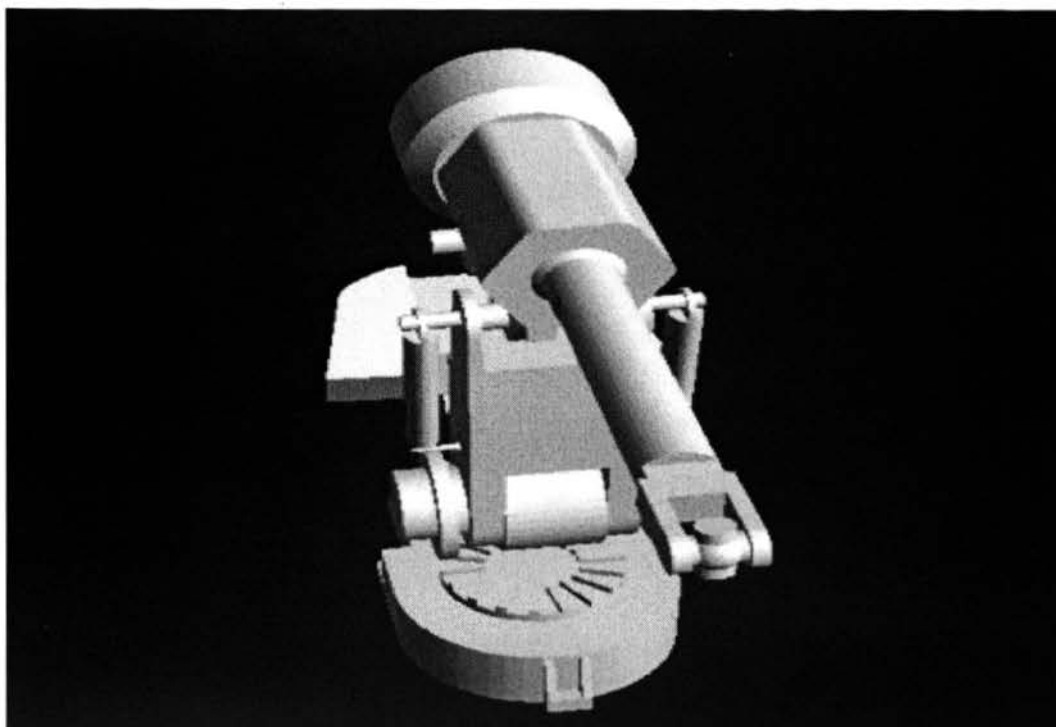This is a configuration text file that is used in the generic representation of a machine such that all data related to the machine like axes, origin etc. are present in it. Machine representation is done in the form of numbers and words. This text document must contain data in columns with each column separated by a tab space. Examples are given for a X and Y table of a CNC machine.

1- Should contain the label for the part(like X or Y or A)

2- Should contain the relation between each part of the machine. The part that is connected to the world space is given -1. The other parts are related by numbers (1, 2, 3, 4 etc.) where in a part given the relation 1 signifies that it is the parent to the part given the relation 2 and so on. This is used to generate the parent – child list which is explained in detail, later on in the paper.

3-5   Specify the origin of the part in local co-ordinates(X, Y, Z), that is   the co-ordinate frame of the part. The origin is (0, 0, 0) by default for STL files that are imported from assembly of the machine. For a random file, the origin is the offset distance between the parts with respect to their local part origins.

6- Must contain the orientation of the each part in the form of degrees in order to place them properly in the world space.

7- Must contain the type of motion (translation or rotation) for the particular part.

8- Must contain the angle of motion for parts that have rotational motion.

9-11 Must contain the vectors of axis of motion in X, Y, Z coordinates for each   part. Always 1 is used to depict motion and zero is used to depict that there is no motion. Example: (1, 0, 0) depicts that there is motion along X axis.

12-14 Must contain the center for rotational motion in global coordinates.

15 Must contain the names of the geometry files to be imported with the path that is the folder in which they are present.

16-19 Must contain the colors in the form of vectors. For example: (1,0,0)-red, (1,1,0)-yellow, (0,0,0)-black,(0,1,0)-green,(1,0.5,0)-orange, (1,1,1)-white,(0,0,1)-blue,(0,1,1)-cyan,(1,0,1)-magenta.

This kind of a configuration text file can be used to describe any machine/equipment easily. For example, consider two tables X and Y, of a CNC machine and a configuration file for the same would be as follows. The text document for the Figure 6 would contain the data as shown in Table 1.

The parts are labeled as Y and X respectively. The Y table is connected to the world and therefore it is designated by -1. The X table is connected to the Y table and hence is designated by 0. The coordinates of the origin for both the parts is (0, 0, 0) as the parts are imported from the assembly of the machine. The orientation of each part in the form of degrees is zero as well. Both the parts have linear motion. The vector of axis of motion for X table is (1, 0, 0) and for Y table it is (0, 1, 0). Since there is no rotation, the rotational part of the text document is not shown. The names of the .STL files to be imported are given as X.STL and Y.STL. Colors are not represented as the default color is used.

Table 1. Example of Machine Configuration

Label	Relation	Origin			Orientation	Motion	Axis of motion			File name
X	0	0	0	0	0	translation	1	0	0	Y.STL
Y	-1	0	0	0	0	translation	0	1	0	X.STL

5. UTILITY DATA STRUCTURES

There are two kinds of data lists that are derived from the configuration text file. One is the parent - child list and the other is a dependency list.

Parent list:

In order to simulate a machine, there is a need to know the parts that move in tandem with each other and the parts that move independent of each other, such that they can all be put in a moving and a non-moving frame respectively while performing simulation. This is nothing but the dependency list. In order to derive the dependency list, the parent – child relationship for each part is to be known. This gives the dependency information required. These lists are generated from the relation list that is given by the user in the configuration text file.

Considering the case of X and Y table from Figure 6, the X table is connected to the world space and Y table is connected to X. Therefore Y is a parent to X. Thus the parent list in this case would be:

$$[2, 1]$$

But, there are bound to be complex cases. For example, in a CNC machine as shown in Figure 6, the column for relation between each part would contain the following data:

$$-1, 0, 9, 10, 8, 1, 9, 3, 0, 7, 4.$$

Then the parent list would be:

$$[[1, 8], [5], [], [7], [10], [], [], [9], [4], [2, 6], [3]]$$

The empty arrays show that their corresponding parents do not have any more children.

Dependency list

For Figure 7, the dependency list would be:

[2, 1]

The motion of the X table is independent of any other part. That is when Y table moves, X table does not need to move. The Y table, however has a motion that depends upon X, that is, when X table moves, Y moves as well. Hence the dependency list generated shows that Y is dependent on X in a numerical format of [2, 1]. Dependency list is nothing but the child list.

For Figure 7, the dependency list would be:
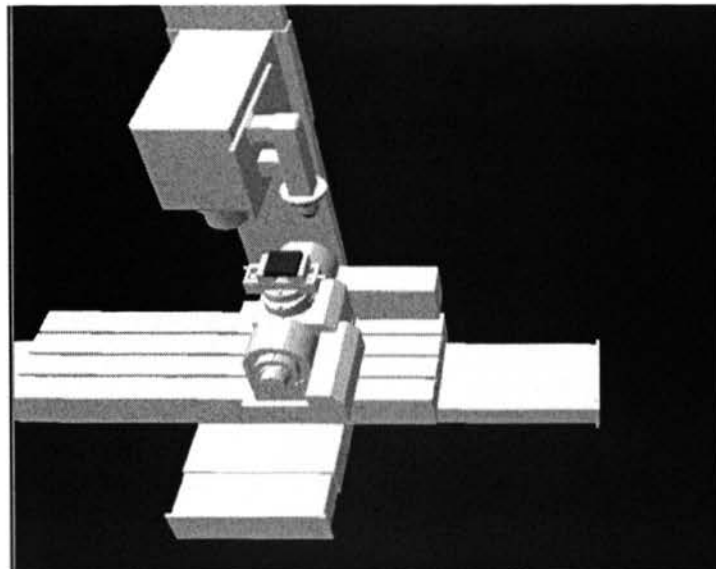
[[1, 5] [8, 4, 10, 3, 7, 9, 2, 6]]

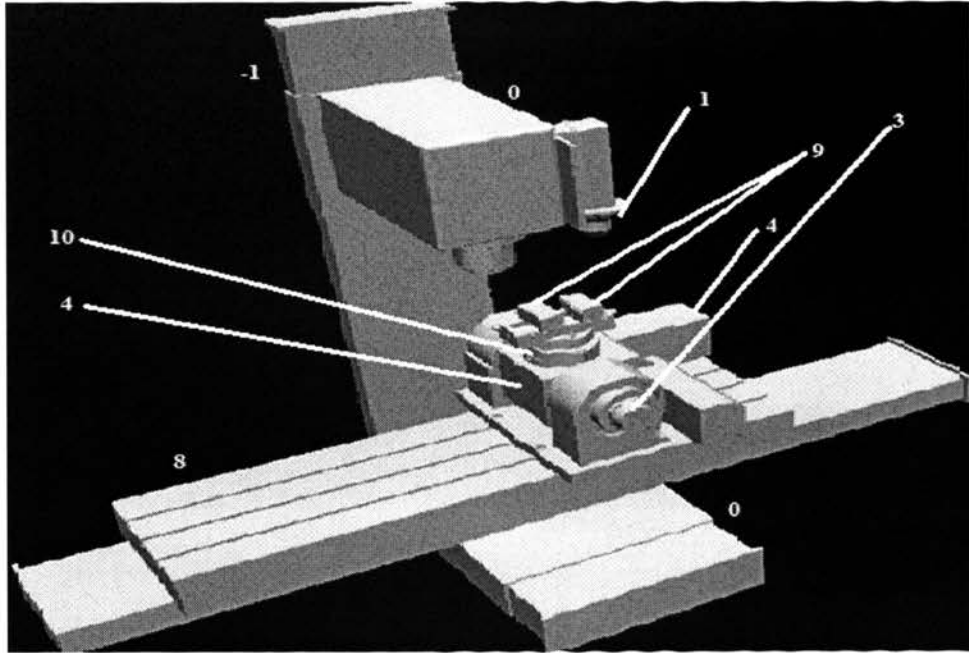Figure 6. Faces Model of 5 Axis CNC Machine

Figure 7. Illustration of Parent-Child and Dependency List

6. TOOL PATH DATA

This is another text document that contains the tool path motion in axial coordinates for n number of axes and the time step for the same in the form of distance points. This text document must contain data in columns with each column separated by tabs.

For a linear 3 axes motion:

- The first column contains the motion of the machine in X direction.

- The second and third columns contain the motion of the machine in Y and Z directions respectively. The Z direction is just the addition of layers over the same path, thus leading to additive manufacturing.

- The fourth column consists of the time step.

Consider Table 2, as an example for the tool path data file. This data represents the path for laser deposition when the motion is translational and it is generic to different paths to be deposited. In case of rotational motion of joints, one more column needs to be added to the file, containing the rotational angle for the joint. One of the examples is the path for LAMP logo as shown in Figure 8.

Table 2. Example of Tool Path Data File

X	Y	Z	T
1	0	0	2
0	5	1	4
2	6	0	6

Figure 8. Simulation of LAMP Logo Deposition

7. VISUALIZATION

The input for this is the dependency list and type of motion. The dependency list helps in giving data regarding parts that move along with a particular one. The type of motion can be either linear or rotational. Linear motion is a straight line motion that can be described using only one spatial dimension. Rotational motion for each joint differs. There are three types of rotational motions:

- Revolute – 1 DOF

- Cylindrical- 2 DOF

- Spherical- 3 DOF[19]

When the same joint has more than one DOF, then it is represented as many times as the number of degrees of freedom in the configuration text file except that its geometry is represented only once and the rest of the representations are considered virtual.

The faces primitive is represented in one of the columns in the configuration file. The tool path text document gives information regarding axial movements. All the above information is used to generate visual simulation of the equipment by placing the parts to be moved at one time step, in tandem in a moving frame and the rest of the parts in a non-moving frame and updating the moving and non- moving frame for each time step.

8. RESULTS

The simulation results are shown in the case of a CNC machine in Figure 9 and Figure 10. Figure 9 shows the linear motion of the X table along with the Vise in the X direction and back. Similarly, Figure 10 shows the linear motion in of the Y table along with the X table and Vise in the Y direction and back. Visual simulation for a prismatic joint can therefore be done for any manufacturing equipment by importing its CAD model and hence, it is not specific to a single machine and is also much more sophisticated. This helps in error checking of the tool path and in turn saves time and money. Thus part repair can be done easily by laser deposition, once the tool path is checked.

Figure 9. Illustration of Linear Motion Simulation Along X- Axis

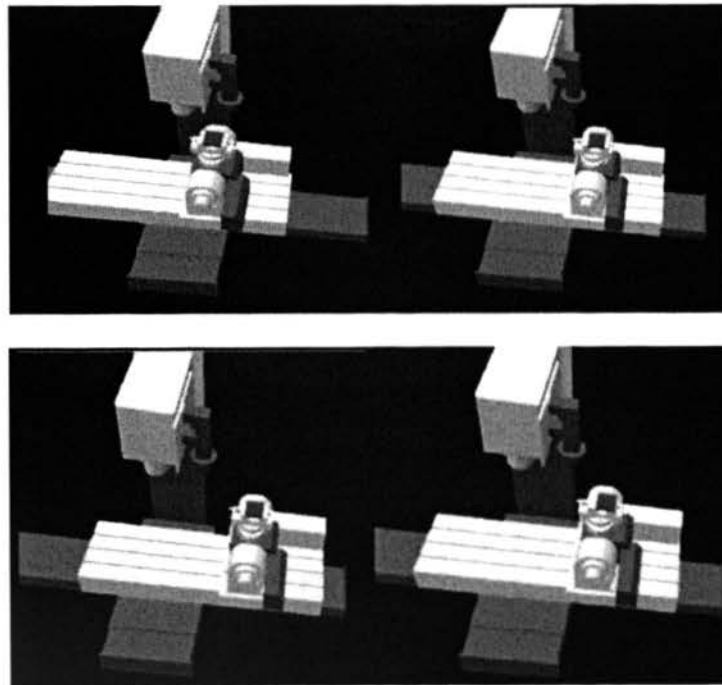Figure 9. Illustration of Linear Motion Simulation Along X- Axis…contd

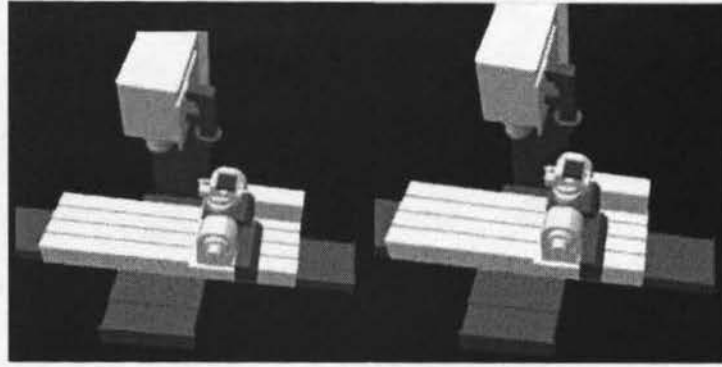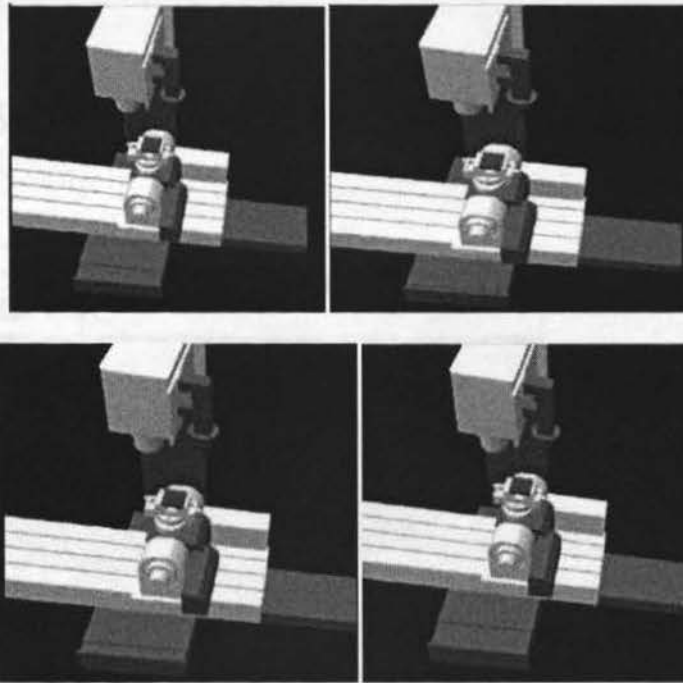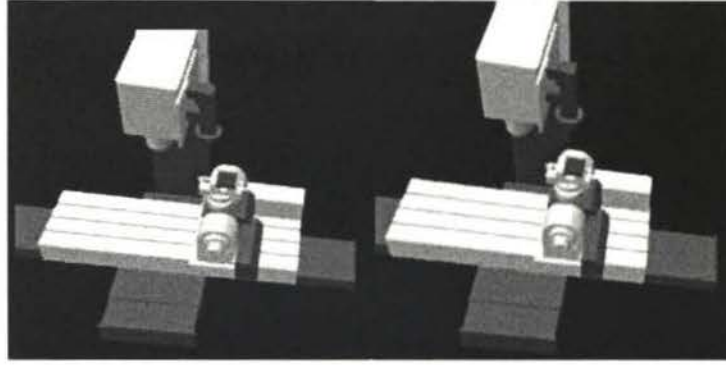Figure 10. Illustration of Linear Motion Simulation Along Y- Axis

Figure 9. Illustration of Linear Motion Simulation Along X- Axis...contd
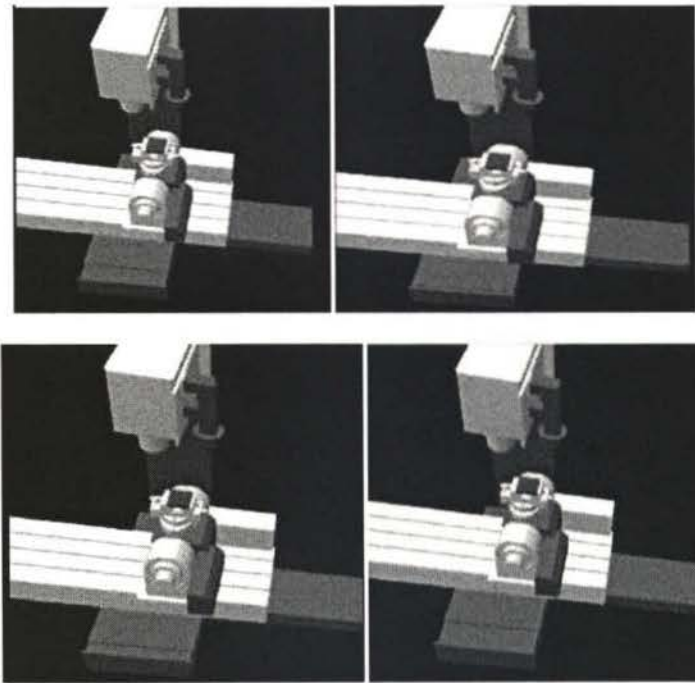

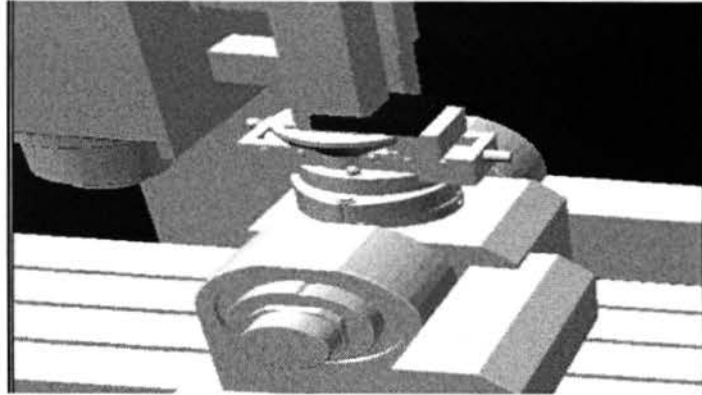Figure 10. Illustration of Linear Motion Simulation Along Y- Axis

Figure 11. Illustration of Collision of Tool Into The Product

10. ACKNOWLEDGMENT

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II. GENERIC KINEMATIC SIMULATION FORVERIFICATION OF LASER METAL DEPOSITION TOOL PATHS

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Abstract

The development of 3D visual simulation tool for machine simulation and deposition validation is a key approach in saving time and reducing cost during part restoration process. The tool path for part repair is generated by a planning system. Hence, it is important to check for collision and validate the tool path before running it on a machine. There are several kinds of manufacturing equipment being used. Therefore, there is a need for the development of a generalized method to visually simulate a variety of machines. Another important use of this tool is simulation of different deposition courses. This paper presents the research conducted on describing machine configuration in a generic format, which gives useful information about the scene, machine statistics and also, data that would aid in the simulation process. This work concentrates on integrating laser deposition simulation to mechanism motion simulation, in order to demonstrate a manufacturing operation. This 3D simulation tool has been

tested on various manufacturing equipment and different deposition tool paths were validated and some of the results are shown in the paper.

1. INTRODUCTION

Layered Manufacturing (LM) technology, also known as Rapid Prototyping (RP) is a process that involves adding raw material, in layers, to create a solid part directly from a CAD model, instead of removing the material as in the case of traditional subtractive manufacturing processes such as machining. LM processes fabricate a physical part in an additive fashion, layer by layer. Direct laser deposition is capable of fabricating fully dense metal parts directly from the CAD model. Such a process has drawn interest from aerospace, heavy machinery and other industries. Due to its complexity, this process requires an automatic planning system to drive it.

Laser Aided Manufacturing Process (LAMP) lab uses a Fadal 5-axis CNC machine (model VMC3016) as shown in Figure 1, as the motion driver. The deposition nozzle is mounted at the side of the spindle, which forms a hybrid manufacturing system on a single workstation. These are used to restore a damaged part to its original geometry.

The final tool path of a machine for laser aided deposition is in the form of G and M codes, which needs to be verified before part repair is performed [12], since the parts are expensive and a small error [1] in the repair action can incur a huge loss. Thus visual simulation of the entire repair process is done before any practical application of the codes that are generated. [2 to 8, 14 to 15]

Laser metal deposition for part repair can be done using other manufacturing equipment as well, some of them having more than five axes. Thus, there is a requirement for a generalized method of simulating different machines, such that the same algorithm can be applied for different kinds of equipment.

This paper aims to address generic visual simulation of different manufacturing equipment. It consists of a summary on the generic machine configuration representation, derivation of a parent list and a dependency list from it and how this helps in visual simulation of machine movement. Varied machine motion simulation is illustrated in the later sections. This study also specifies the format for a machine motion file (tool path) and depicts some of the deposition paths
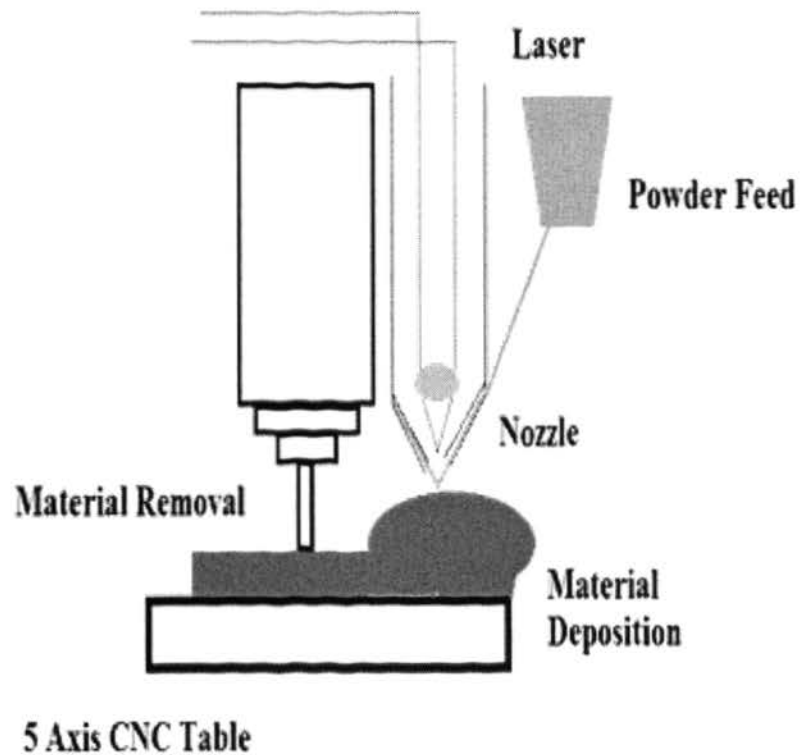

Figure 1. Laser Metal Deposition Process

2. RELATED WORK

Visual simulation is still very much focused on a single machine or equipment and or is specific to a group of machines. Even though visual simulation of machines is being done since a long time, it has been having a very simple representation of the simulation environment. Also, the solids used in simulation are simple and not sophisticated. [13] Following are some other simulation softwares available:

- LINCAGES (Nelson and Erdman 1994), Sphinx (Larochelle et al.1993), SPADES (Larochelle 1998) and Synthetica (Suet al. 2002) : Mechanism design software focus on the dimensional synthesis of planar, spherical or spatial linkages. They do not have interface for constructing mechanisms and simulating their motion.

- WATT by Heron Technologies Inc., SyMech by symech.com and Ch Mechanism Toolkit by SoftIntegration Inc. (Cheng and Trang 2006): These focus on the analysis and synthesis of planar 4-bar , 6-bar or 8-bars. None of them provide a full dynamic simulation for general mechanisms

- Working-Model (Design Simulation Technologies Inc.) and ADAMS (MSC Software Co.): Provides versatile functionalities in modeling and simulating mechanisms. WorkingModel does not support spatial mechanisms, and it does not provide an advanced visualization and interaction functionality. ADAMS does not provide a user-friendly interface.

- MATLAB's SimMechanics: Provides a powerful multi-body dynamics solver. However, its building process is based on block diagram, which is not intuitive (see what is built), and is overly complicated.

- VRJuggler , Wizard Virtual Reality,Virtual Reality Peripheral Network (VRPN), Virtual Assembly Design Environment (VADE), MIVAS: A Multi-modal Immersive Virtual Assembly System, SHARP: a Dual-Handed Haptic Assembly System, Virtual environment for assembly training : Relatively less work has been done for applying VR techniques in supporting interactive design especially the conceptual design stage.

- Virtual environment (VE): The main focus is not on the construction of mechanical systems but on the dynamic simulation aspect.

- Stan et al. (2008) have developed a VR, for a particular type of parallel robot, by using the MATLAB's VR toolbox, which does not provide a 3D stereoscopic immersive visualization.

- VR programs dedicated to the design of spherical mechanisms (Furlong et al. 1999) and spatial mechanisms: The focus of these works is on a specific kind of mechanisms, spherical 4R or spatial 4C, etc., not on providing an intuitive and user-friendly interface for generic simulation of mechanisms.

- CG Vericut is dedicated to process planning for machining and only deals with CNC's. It does not facilitate simulation of additive manufacturing or other machines. Another drawback is that it cannot be used to simulate robots or other manufacturing equipment.

- DELMIA IGRIP focuses on processes like spot welding, painting, arc welding. Siemens Technomatix is a solution to validate and manage detailed product and process data. However, both these applications do not serve their purpose in case of layer manufacturing.

- The original goal of the OROCOS effort was to address general mechanical system representation for robotics applications. But, the Kinematics Package in OROCOS is at the design concept stage and no software has been developed yet.

- OSCAR is used to generic modeling and simulation of serial manipulators, with the main intention of being an education tool. [22]

Thus, there is no tool that has the following features:

(1) Generic representation of serial mechanisms scriptable by the user

(2) Integration of deposition validation with machine simulation

(3) Complex mechanism simulation ability, not specific to a particular type

This paper describes a generic method that has been developed to represent a machine, in the form of numbers and letters in a text document. This could be used for any given serial machine configuration. Also, a CAD model [16] of the machine can be imported and hence complex structures can be visually simulated. This paper also depicts laser metal deposition as a key example of additive manufacturing process.

3. GENERALIZED SIMULATIONS OF VARIOUS MACHINES

Figure 2 shows an overview of how generalized simulation tool works. There are three inputs to the algorithm- one is a 3D CAD model of the machine as shown in Figure 3, second is the tool path or machine motion document and the third one is a machine configuration file. Other than this, a frame rate is also given as an input. The details of each of these would be discussed later in the paper. The following page has a summarized description of the entire simulation process.

The 3D CAD model of the machine should be given as an input to the simulation tool in STL format. This format describes only its surface model, which is widely used for rapid prototyping and computer aided manufacturing. This is then converted to a faces object, as shown in Figure 4.

Based on the 3D CAD model, the machine configuration file is written and given as an input to the simulation algorithm. The raw data in this file is descriptive information about the machine. This data is transformed into a set of data lists such as parent list, dependency list and motion list. Although raw data can be viewed directly, data lists are a vital intermediate step when the data is abstract. This model also points out the need to transform raw data into something more usable [9].

The motion configuration file is one more important input given to the simulation tool. This file gives information regarding the displacement of various axes of the manufacturing equipment. It also gives details about the machine operation. Using the 3D CAD model of the equipment, data from the machine configuration file and the motion file the machine can be simulated.
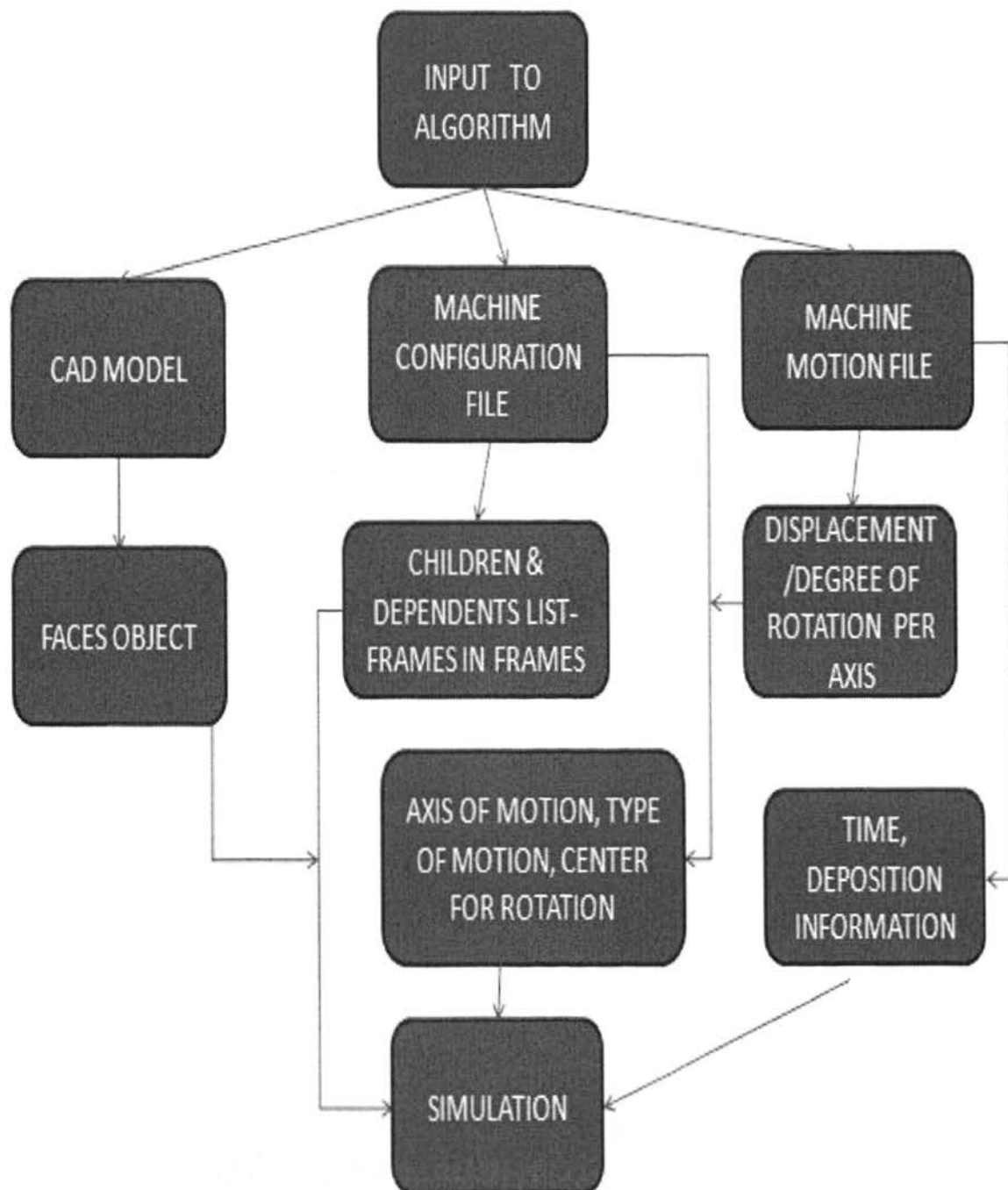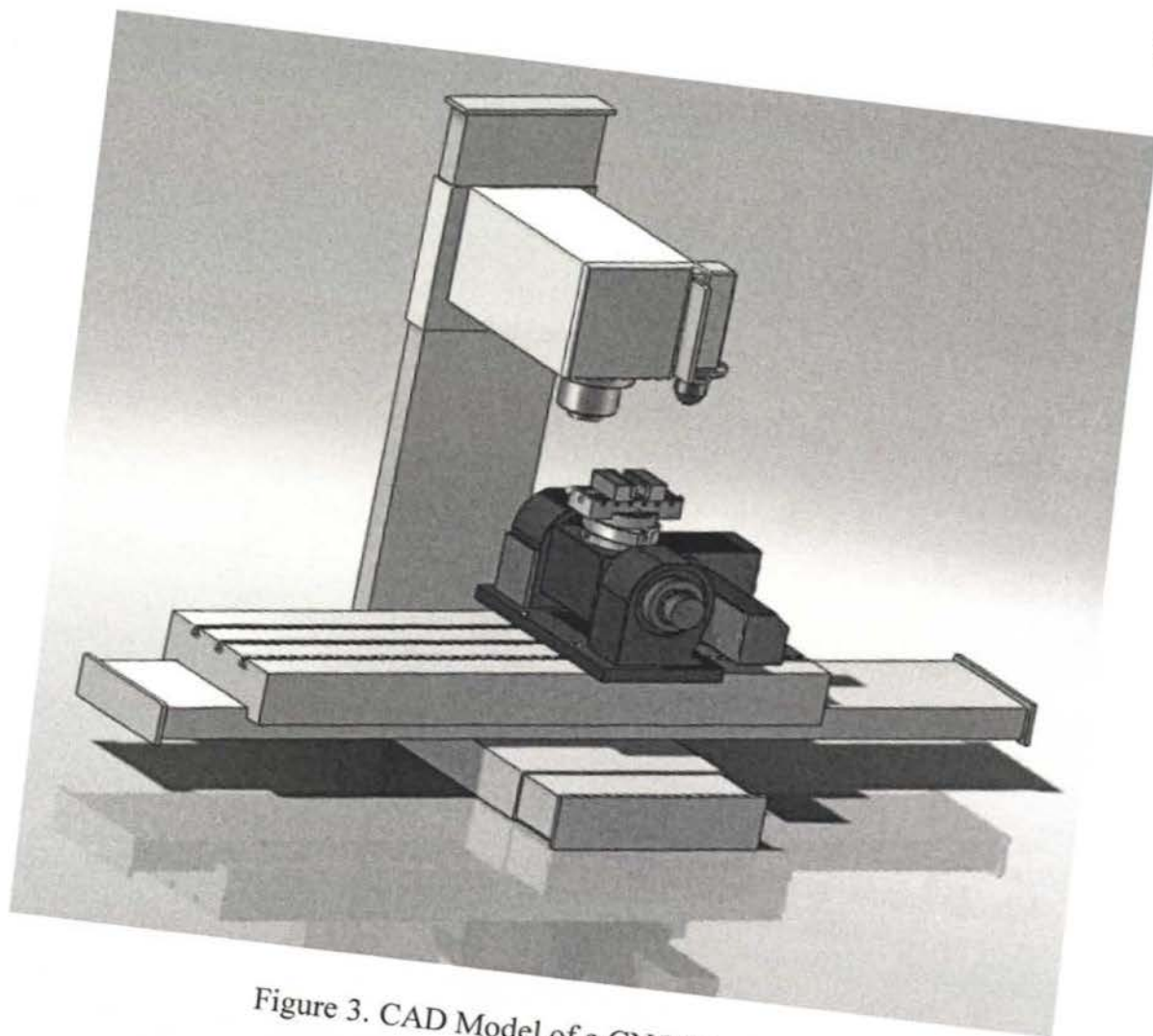
Figure 2. Flowchart of the Simulation Process
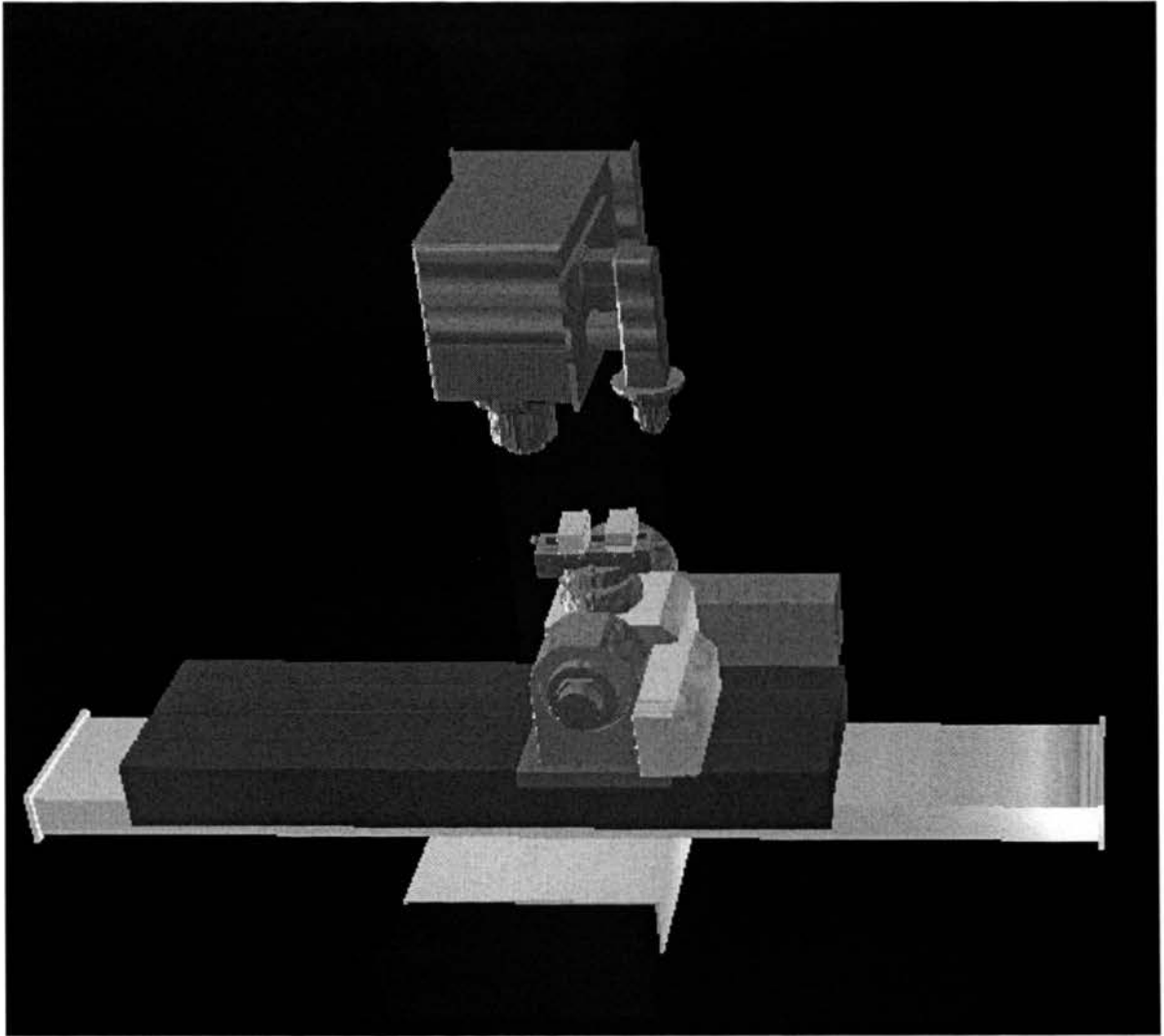
Figure 3. CAD Model of a CNC Machine

Figure 4. Faces Model of a CNC Machine

4. MACHINE CONFIGURATION DATA

This file is used to describe the machine and provide information related to it as well as enhance its visual appearance. This configuration file is used as a generic representation for different machines such that all data related to the machine like axes, origin etc. are present in it.

Machine representation is done in a text document format in terms of numbers and words. This text document contains data in columns with each column separated by a tab space. Example of a machine configuration file is given for a few axes of a CNC machine.

The following is the set of data contained in each row of the configuration file:

1 Contains the title of the simulation display like CNC

2 Represents the length of the simulation scene in terms of a number like 1000

3 Specifies the width of the visual display in terms of a number like 800

4 Gives the direction for rotation of the machine such that it is positioned in the right direction

5 Provides a means to turn the world space up and is mentioned as a vector like 0, 1, 0 [20]

6 Labels of the set of parts that have motion, in the same order as in the machine motion file

7 Specifies the coordinates where deposition begins. In case of no deposition, 'no_dep' is used.

8 Represents the units of the deposition points as 'in' or 'mm' for inches or millimeters respectively.

9 Information regarding the points – 'abs' for absolute, 'rel' for relative

10 Deposition happens in the form of cubes. The cube size is therefore specified by the user.

The following is the information on the data contained in each column of the machine configuration file given against the column numbers as follows:

(1) Contains the label for the part (like X or Y or A)

(2) Specifies the relation between each part of the   equipment. The part that is connected to the world space is given -1. The other parts are related by numbers (1, 2, 3, 4 etc.) where in a part given the relation 1 signifies that it is the child to the part one and so on. This is used to generate the parent list which is explained in detail, later on in the paper

(3- 5) Specifies the origin of the part in global co-ordinates (X, Y, Z), that is the co-ordinate frame of the entire machine. The origin is (0, 0, 0) for STL files that are imported from the assembly of the machine. For a random file, the origin is the offset distance between the machine's origin and the local part origin

(6) Lists the orientation of the each part in the form of degrees in order to orient them properly in the world space. The orientation angle is N if the machine files are imported from the CAD assembly. However, if the files are randomly imported and need to be assembled, the angle can be given in terms of numbers as 90

(7) Contains the type of motion (translation or rotation) for the particular part. If the part has linear motion, then 'trans' is used to describe it. For rotational motion, 'rot' is used and when there is no motion, 'nil' specifies it

(8-10) Describes the vectors of axis of motion in X, Y, Z coordinates for each part that has motion. Always 1 is used to depict motion and zero is used to depict that there is no motion in that direction. Example: (1, 0, 0) depicts that there is motion along X axis

(11-13) Specifies the center for rotational motion in global coordinates as a vector. Example: (100, 0,100)

(14) Contains the names of the geometry files to be imported with the path that is the folder in which they are present.

(15-17) Gives the colors of the parts in the form of vectors. For example: (1,0,0)-red, (1,1,0)-yellow, (0,0,0)- black,(0,1,0)-green,(1,0.5,0)-orange,(1,1,1)-hite,(0,0,1)-blue,(0,1,1)-cyan,(1,0,1)-magenta[20]

This method can be used to describe any machine/equipment easily. For example, consider X, Y and Z axes of a CNC machine as shown in Figure 5. The configuration file for the same would be as in Table 1.

The parts are labeled as X, Y and Z respectively. Part Z and Y are both connected to the rails which in turn are connected to the world space. The rails do not have any motion. Part Z and Part Y have no parent – child relationship between them. Therefore, their motion also is not connected. Part X, however is a child of Part Y. That is, when Part Y moves, X also moves along with it, but the opposite is not true. Now the same is depicted in the Table 1.

The set of data contained in each row of the Table 1 is the title of display – 'simulation', length of the scene – '1000', width of the display – '800', direction for rotation of the machine – 0,0,-1, to turn the world space up – 0,1,0, labels of the set of

parts that have motion- 'X, Y, Z', last second column in machine motion file – 't', last column in machine motion file – 'mop'. The machine motion file would be explained later in the paper.

The data in some columns of the machine configuration file is explained below:

(2) Relation - Since Rails is connected to world space, it's given '-1', since Y and Z are both connected to Rails, their relation is '0' and since X is a child to Y, its relation is '2'

(3- 5)Origin of the part – Since the parts have been obtained from an assembly, their origins are all (0, 0, 0)

(7) Type of motion – 'nil' for Rails and 'trans' for X, Y and Z.

(13-15) Center for rotational motion- (0, 0, 0) for all parts since none of them have rotational motion.
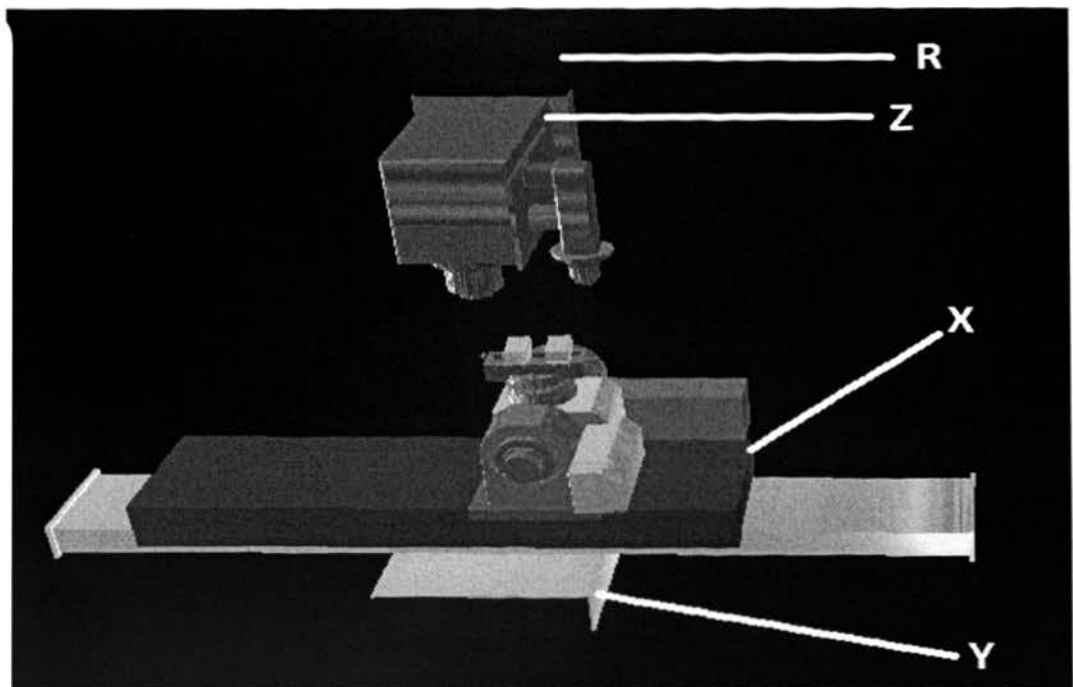

Figure 5. X, Y & Z Axes of a CNC Machine

Table 1. Example of Machine Configuration File

Name	Relation	Origin			Orientation	Motion Type	Axes of Motion			Center of Rotation			File name	Color Vector		
Sim																
1000																
800																
0	0	1														
0	1	0														
X	Y	Z														
9	1	1														
in																
abs																
2	2	2														
R	-1	0	0	0	0	Nil	0	0	0	0	0	0	R.Stl	0	0	1
X	2	0	0	0	0	Trans	1	0	0	0	0	0	X.stl	1	0	0
Y	0	0	0	0	0	trans	0	1	0	0	0	0	Y.stl	1	1	1
Z	0	0	0	0	0	Trans	0	0	1	0	0	0	Z.Tstl	1	1	1

5. UTILITY DATA STRUCTURES

There is a data list that is derived from the configuration file called the children list. Dependents list is obtained by manipulating the data in the children list. These lists are important for the purpose of placing frames inside frames and thus aids in the main simulation.

Children list:

In order to simulate a machine, there is a need to know the parts that move in tandem with each other and the parts that move independent of each other, such that they can all be put in a moving and a non-moving frame respectively while performing simulation.

Considering the case of X and Y table from Figure 5, the X table is connected to Y. That is, when X moves, Y does not exhibit any motion. But, when Y moves, Part X moves along with it. Therefore Y is a parent to X. Thus the children list in this case is:

$$[[2, 3], [], [1], []]$$

This shows that Y and Z are children of Rails and Y is a parent to X. But, there are bound to be complex cases. For example, in a CNC machine as shown in Figure 6, the column for relation between each part would contain the following data:

$$-1, 0, 9, 10, 8, 1, 9, 3, 0, 7, 4.$$

Then the parent list would be:

$$[[1, 8], [5], [], [7], [10], [], [], [9], [4], [2, 6], [3]]$$

The empty arrays show that their corresponding parents do not have any more children.

Dependents list:

This is a list of all the children for a specific parent. For example, in Figure 7, the dependents list for the X-table would be:
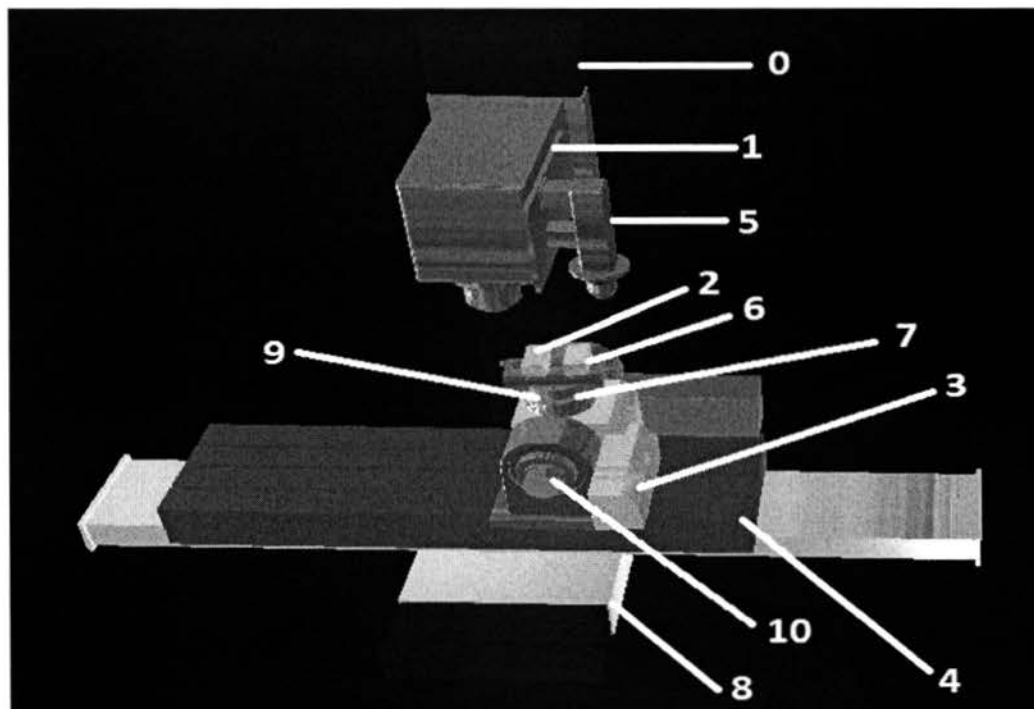
[10, 9, 7, 3, 2, 6].

Figure 6. Illustration of Parent–Child & Dependency List

6. MACHINE MOTION AXES

The type of motion can be either linear or rotational. Linear motion is a straight line motion that can be described using only one spatial dimension. Rotational motion for each joint differs. There are three types of rotational motions:

- Revolute – 1 DOF

- Cylindrical- 2 DOF

- Spherical- 3 DOF[19]

When the same joint has more than one DOF, then it is represented as many times as the number of degrees of freedom in the configuration text file except that its geometry is represented only once and the rest of the representations are considered virtual.

The data about the type of motion of the axis is used to form a list of axes with translational and rotational motions. This is used to identify the type of motion for a particular axis.

7.   FRAMES IN FRAME CONCEPT

Each part of the machine is assigned a particular frame. However, since some parts move in tandem with one another, the children frames are placed in the parent's frame. For the CNC machine, frames in frame concept is shown in Figure 7.
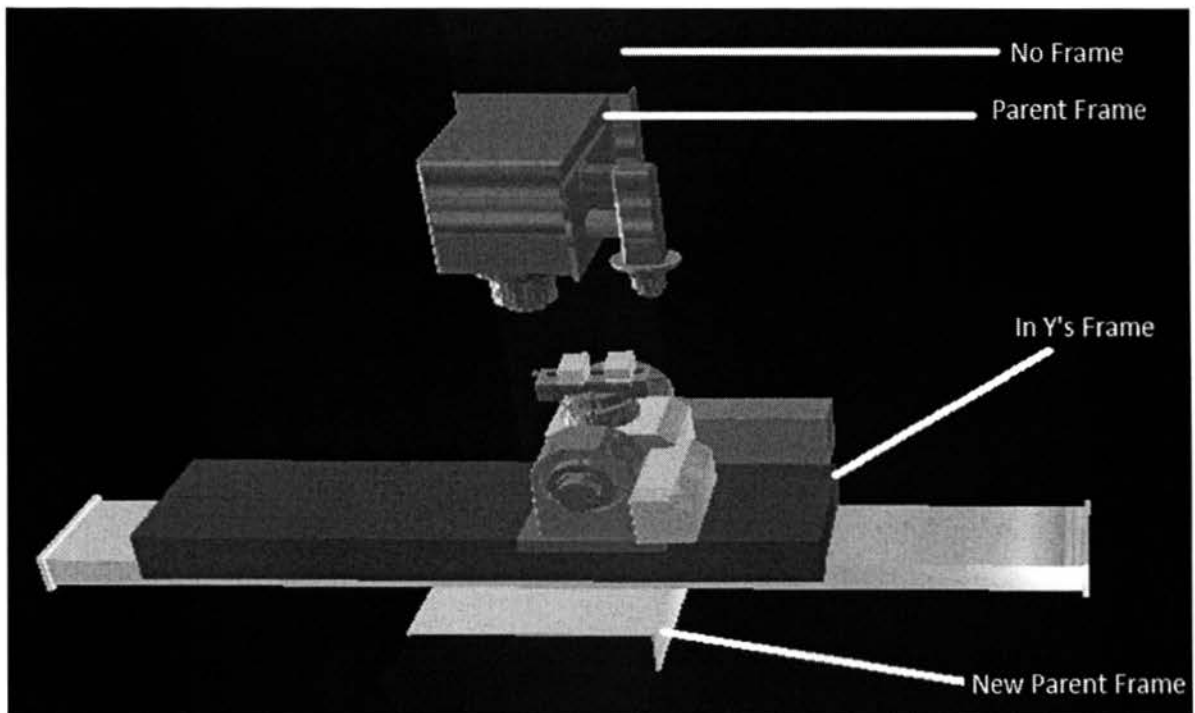

Figure 7. Portrayal of Frames in Frame Concept

8. MACHINE MOTION FILE

This is another document that contains the tool path motion in axial coordinates for n number of axes and the time step for the same. It also contains the data for machine operation. This text document must contain data in columns with each column separated by tabs.

The columns corresponding to the axes contain the displacement for translatory axes and the degree of rotation in radians for rotatory axes. The next column after the axes contains the time for the motion to take place. The second last column contains the laser power index and the last column contains whether the powder feeder is on or off. Deposition takes place when the product of laser power index and the powder feeder data is not equal to zero.

For a linear 3 axes motion:

- The first column contains the motion of the machine in X direction.

- The second and third columns contain the motion of the machine in Y and Z directions respectively.

- Z direction is just the addition of layers over the same path, thus leading to additive manufacturing.

- The fourth column consists of the time step.

- The fifth column has the laser power index

- The sixth column contains the powder feeder on/off data

Consider Table 2 as an example for the tool path data file. This data represents the path for laser deposition of a straight line from (0, 0, 0) to (0, 5, 0). A more complex example is the path for LAMP logo as shown in Figure 8.

Table 2. Example of Tool Path Data File

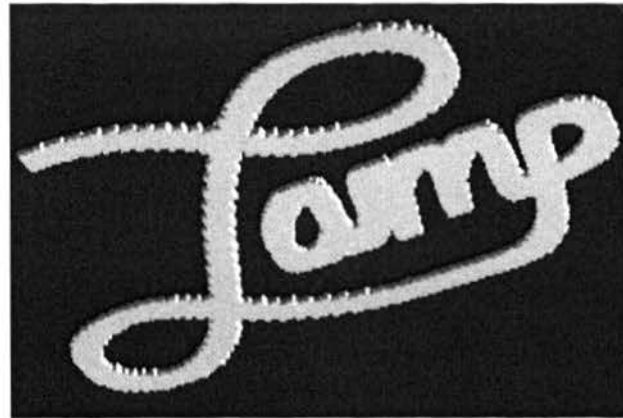| X	Y	Z			
0	0	0	1	10	1
0	5	0	2	20	2

Figure 8. Simulation of the LAMP Logo Deposition

9. TRANSLATION & ROTATION

The order of axes to move is obtained from the machine motion file. In case of translation, the displacement is taken from the data in the machine motion file and the vector of motion is obtained from the machine configuration file, in order to translate the part in the specified direction.

Similarly, for rotation, the degree of rotation is mentioned in the machine motion file and the vector of motion and center for rotation are drawn from the machine configuration data. It's the parent frame that's always translated or rotated and all the children move along with it.

10. VISUALIZATION

The distance/degree to move for each time step is calculated. For each time step, the parent axes frames are either rotated or translated as per the calculated value. In case of deposition, if the product of laser power index and powder feeder data is not zero and the angles are equal, then the length of the deposited cube is increased to give a smoother appearance. If the product of laser power index and powder feeder data is zero, then there is no deposition. If the calculated angles are not equal, then a new cube is deposited.

11. ANALYSIS OF THE TOOL

The time taken to generate a deposition tool path as shown in Figure 8 is 221 seconds virtually. It could be reduced down as required. But the time taken in real time would be more taking into consideration the time for initial setting up of the machine. Thus this tool helps in saving time. The results in section 13 show that, this algorithm can be applied to several serial mechanisms and it can be used to visually simulate machines. Table 3 gives a numerical analysis linking frame rate, time taken to simulate, line length if the time to be taken in the machine motion file is kept constant at two seconds and the frame rate and line length are varied.

Table 3. Numerical Analysis

Serial Number	Frame-rate	Line length(mm)	Time taken to simulate(seconds)
1	10	5	2
2	20	5	2
3	30	5	2
4	10	10	2
5	10	15	2

12. MOVE METHOD

The cube size plays a major factor in the accuracy of the deposition. When there is no deposition, the axes translate/ rotate to the specified points. A flag check is performed for the using the product of the laser power index and powder feeder data.

In case of deposition, the Euclidean distance [21] between the previous and the present axes values is calculated using the formula:

$$Euclidean\ distance\ (p, q) = \sqrt{(q_1 - p_1)^2 + (q_2 - p_2)^2}$$

This distance divided by the cube size gives the number of cubes to be deposited:

$$Number\ of\ cubes\ to\ be\ deposited = \frac{Euclidean\ distance}{Size\ of\ cube}$$

Thus, the position of the cube is incremented from the current position to the next position by linearly interpolating the distance between the two points and adding it to the present cube position. The increment value added has a positive or negative sign as per the region in which they lie in the coordinate axes frame. This is decided by finding the value of the angle between the current and the previous positions as shown in the formula below:

$$Angle = ArcTan2\ (\frac{y2 - y1}{x2 - x1})$$

13. MECHANISM SIMULATION RESULTS

Figure 8 shows the motion simulation of a 5-axes CNC machine. Figure 9 presents the simulation of Nachi robot axes as per the machine motion file in Table 4. Visual simulation can therefore be done for any manufacturing equipment by importing its CAD model and hence it is not specific to a single machine and is also much more sophisticated.
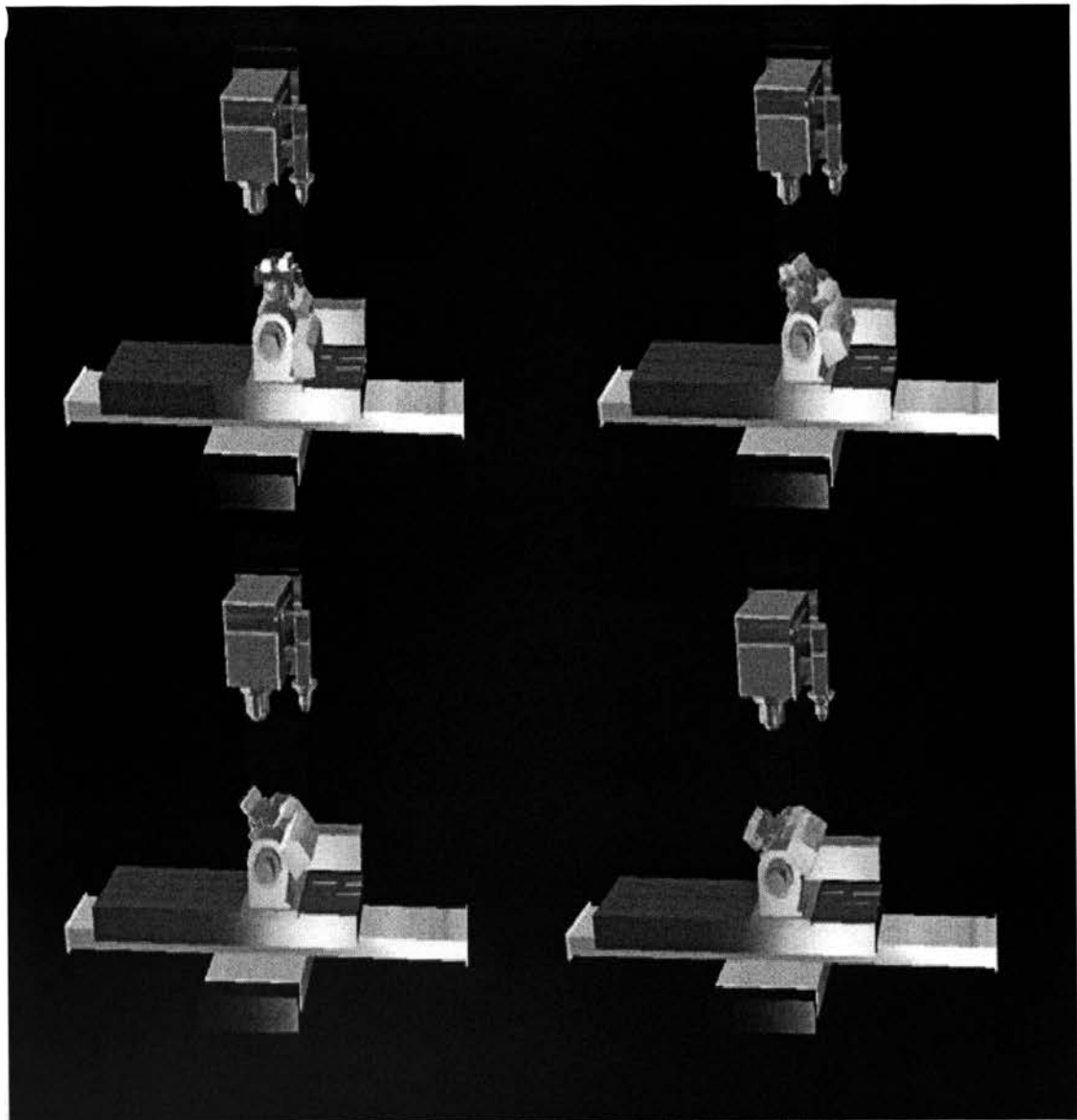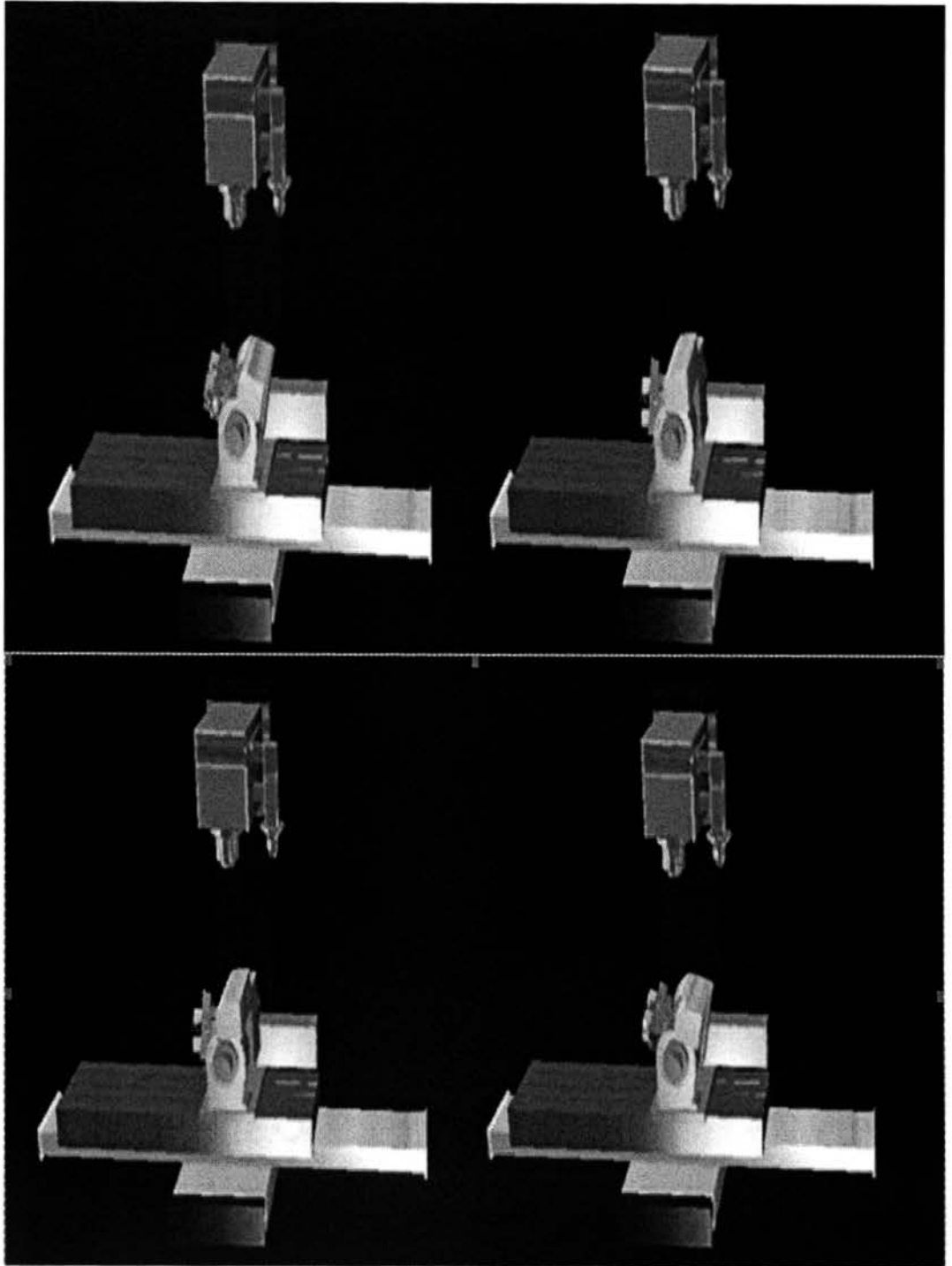

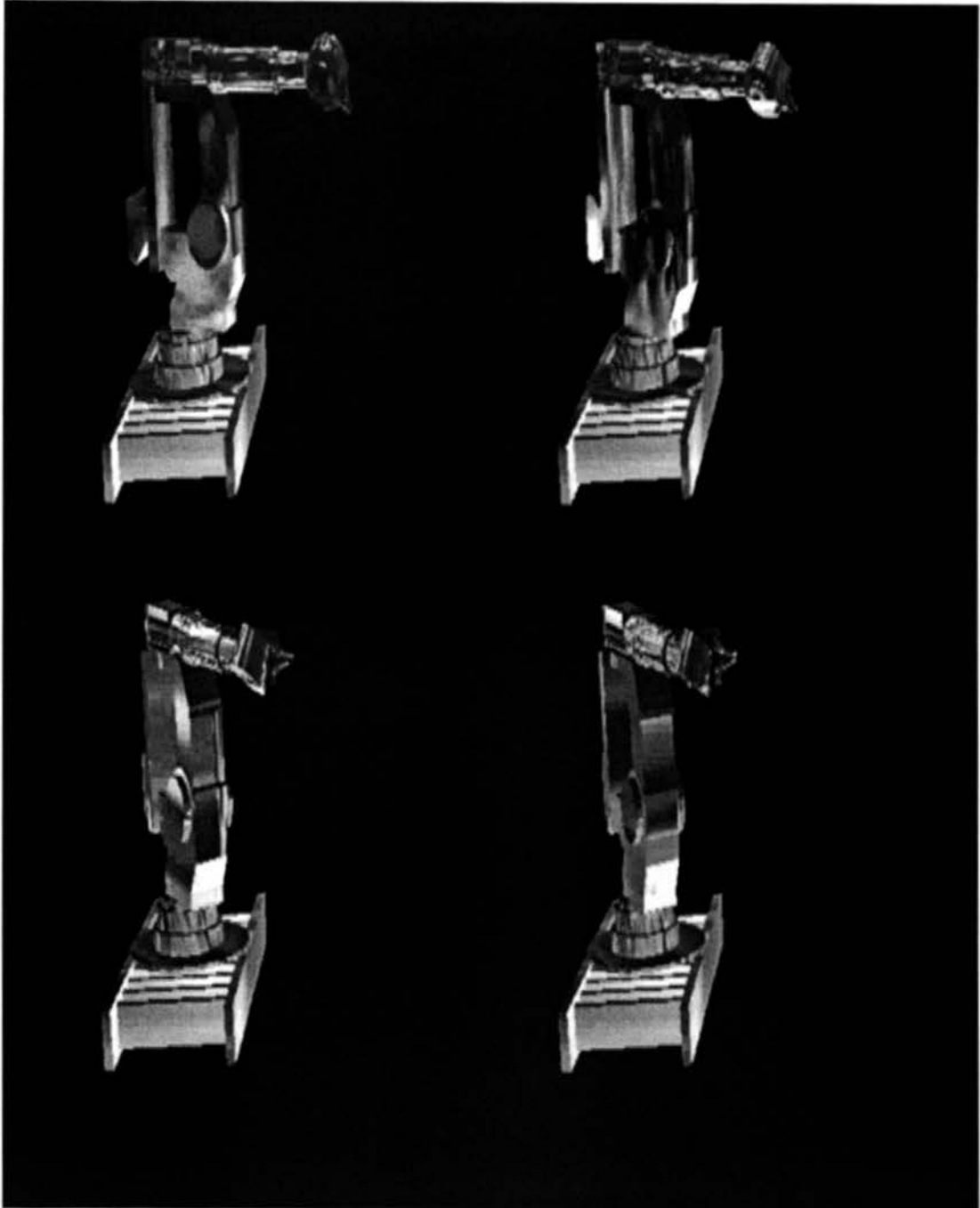Figure 9. Illustration of CNC Axes Simulation

Figure 9. Illustration of CNC Axes Simulation ...contd

Figure 10. Illustration of the Simulation of Nachi Robot Axes

Table 4. Machine Motion File for Nachi Robot in Figure 10

Base	Body	Arm	Wrist	Time	Laser Power	Powder Feeder
-2	0	1	0.5	2	0	1
-4	0.025	2	1	4	0	1
-6	0.05	3	1.5	6	0	1
-8	0.01	4	2	8	0	1

14. DEPOSITION & VALIDATION RESULTS

This tool helps in error checking of the tool path and in turn saves time and money. Thus part repair can be done easily by laser deposition, once the tool path is checked. Figure 11 shows the picture of the part to be deposited. Figure 12 shows the part after deposition with an error in the tool path. Figure 13 shows the simulation of the deposition process in layers for a machine motion file with no error and real life deposition process is shown in Figure 14. Figure 15 shows a part that requires rotation of the B- axis of a CNC machine and depicts an overhang part.
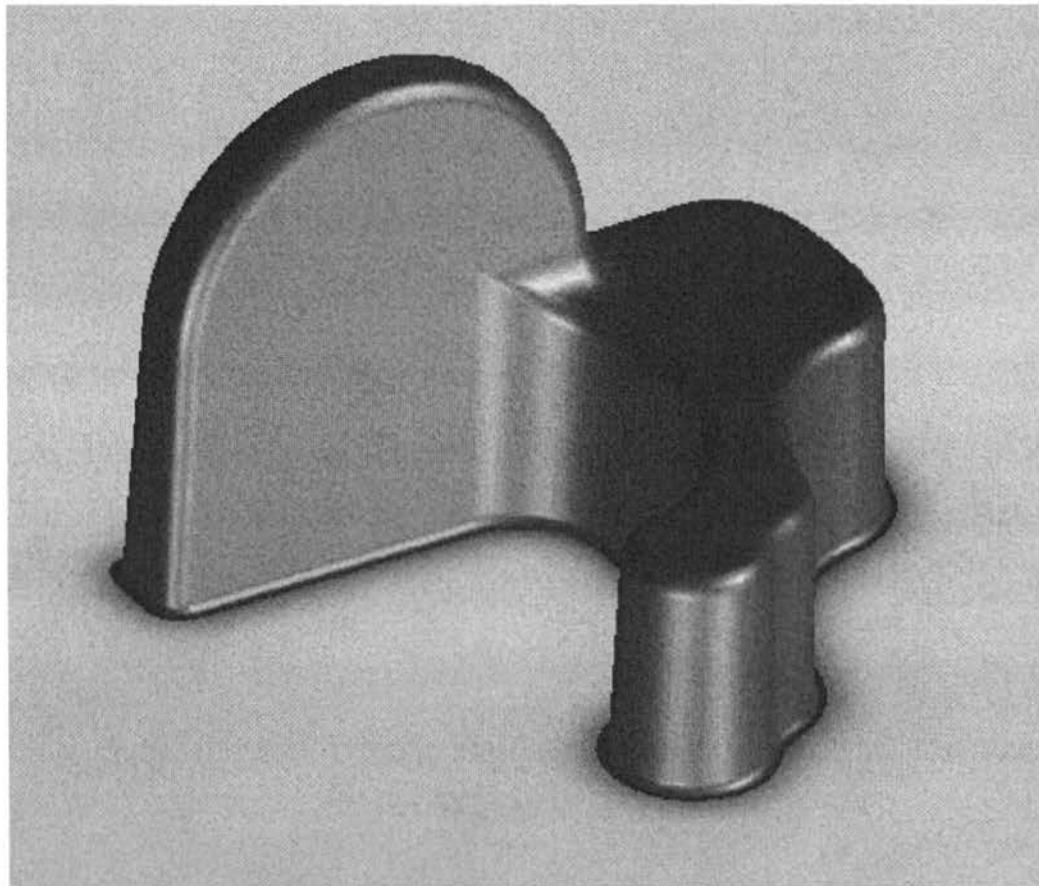
Figure 11. Part to be Sliced by the Planning System
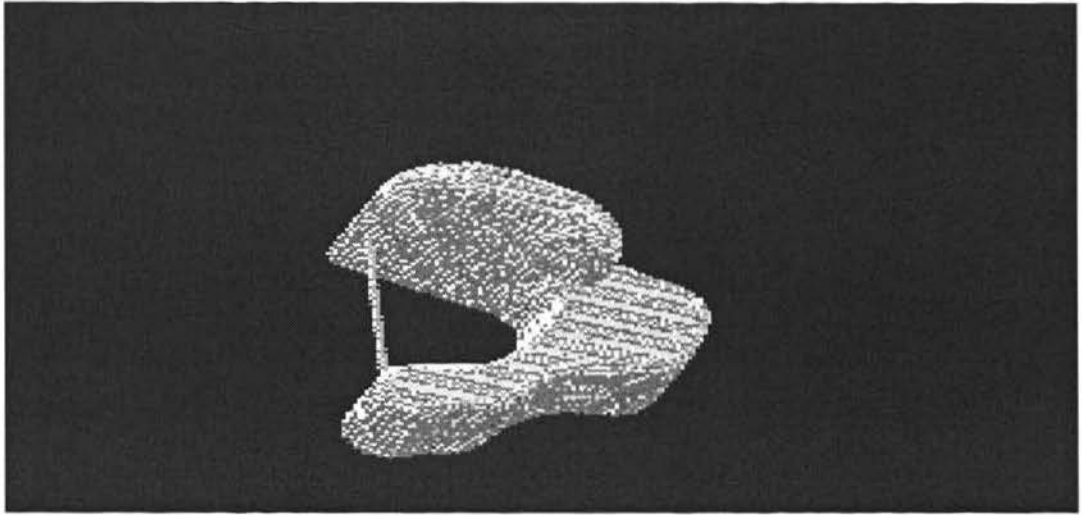
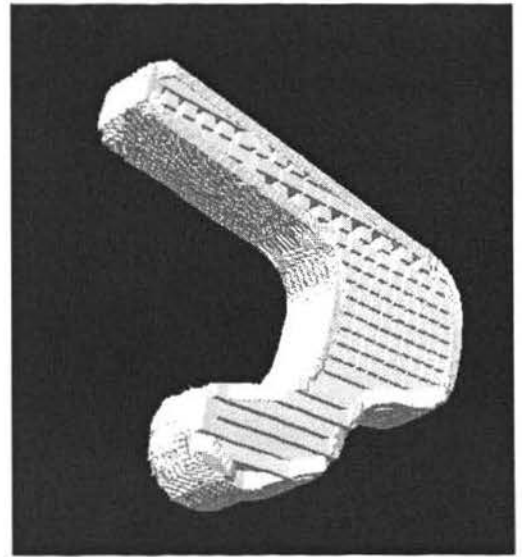Figure 12. Deposition of the Part with an Error in the Tool Path
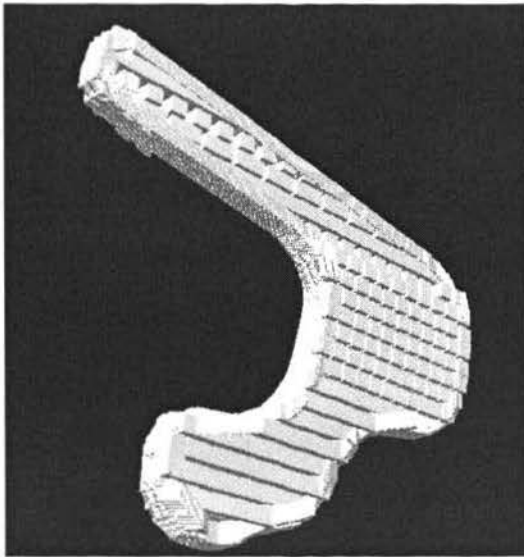

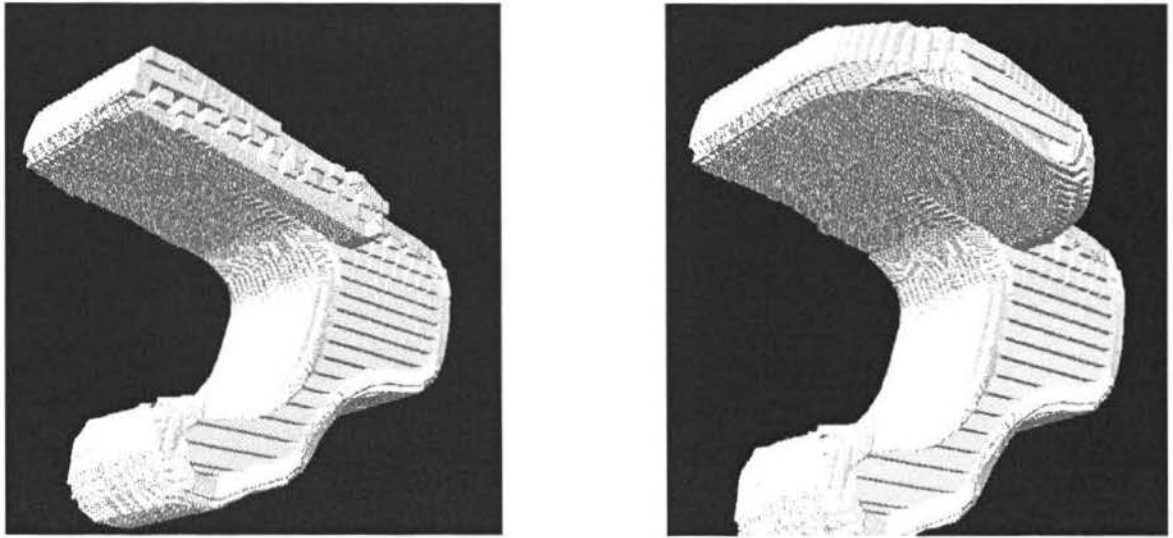Figure 13. Illustration of Part Deposition in Layers

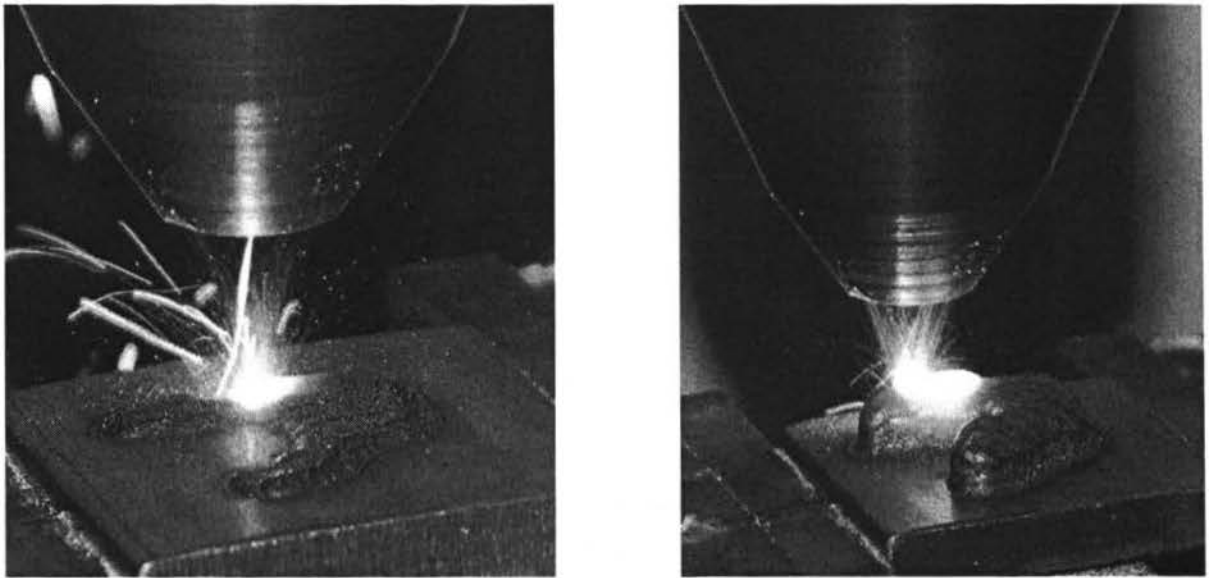Figure 13. Illustration of Part Deposition in Layers ..contd
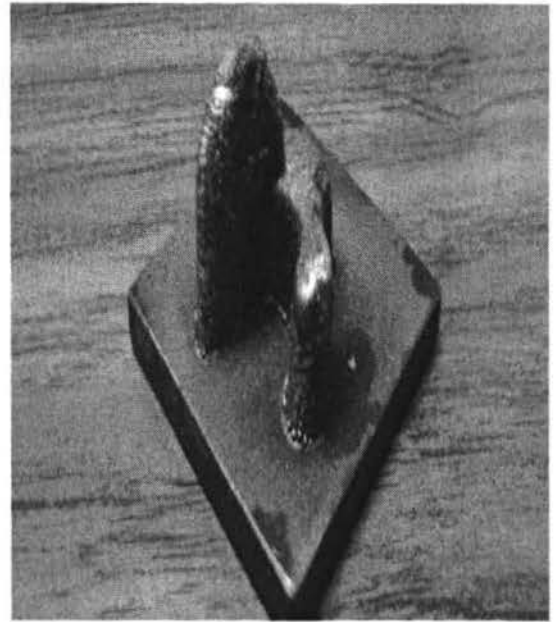

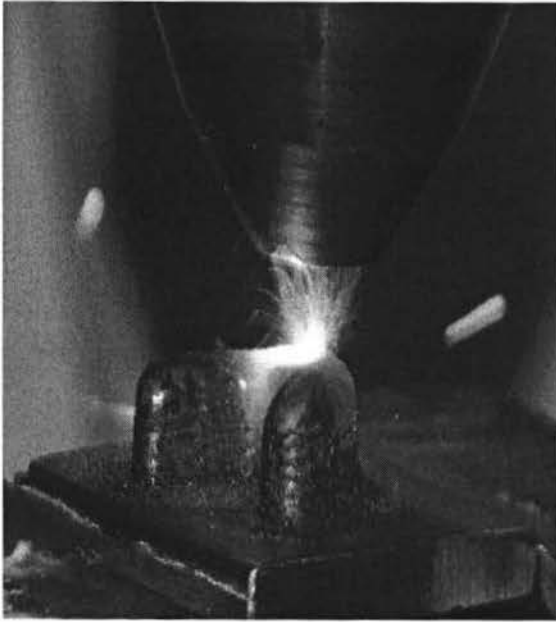Figure 14. Real Life Deposition of the Part

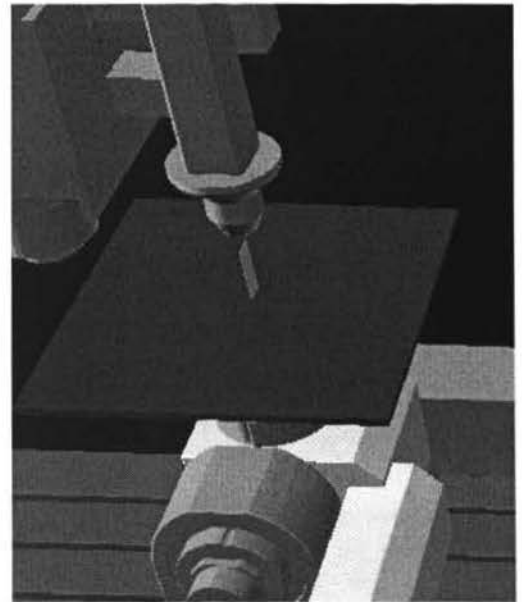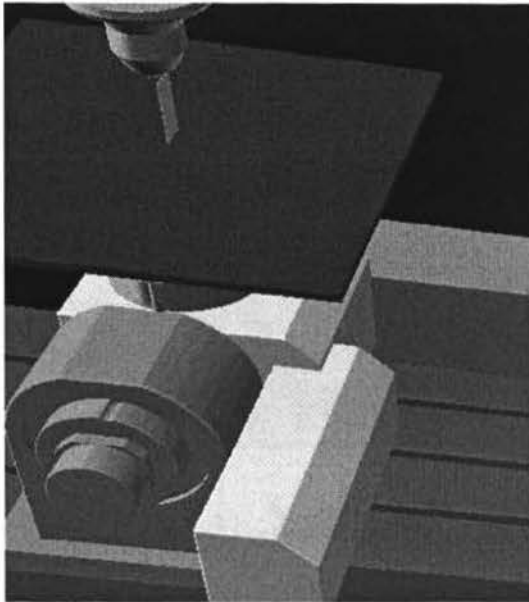Figure 14. Real Life Deposition of the Part ..contd

Figure 15. Illustration of the Overhang Part Deposition in Layers

15. ADVANTAGES

- This tool describes a method to represent various serial mechanisms in a generic format. This format is used as an input for the simulation of the machine

- It can be used by anyone as it has a simple and easy approach

- The algorithm developed aids in the kinematic simulation of various machine movements

- It also helps in simulating the deposition process

- Aims at checking motion and collision as well as the deposition tool path

- Reduces the time spent on setting up a machine for deposition

- Reduces the cost of making an error on an expensive part, in case of an incorrect tool path

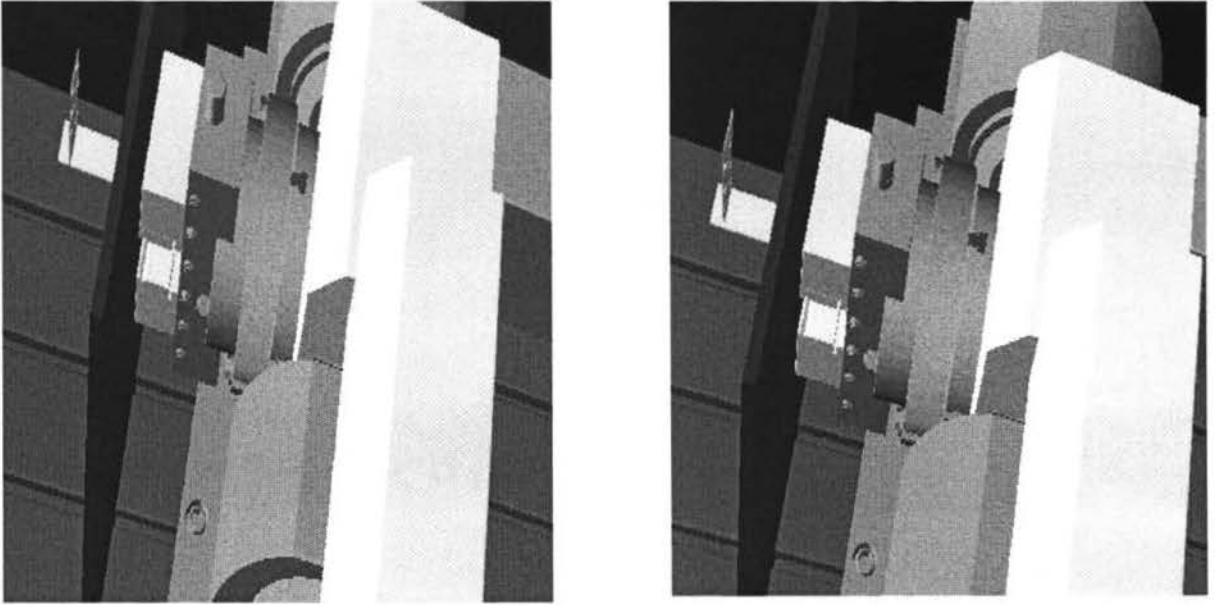- The tool can be widely used as a validation tool for a tool path

Figure 15. Illustration of the Overhang Part Deposition in Layers… contd

16. CONCLUSIONS & FUTURE WORK

The uniqueness about this tool is that it can be used to kinematically simulate varied serial mechanisms as well as validate varied deposition tool paths for CNC machines. The main aim of the tool is to check errors in the tool paths and to avoid wastage of materials. The difference that underlies this approach is the style in which the machine is being represented in the system. That is, this technique uses a knowledge base of the machine data in order to implement the frame based concept.

In building a simulation tool for different kinds of mechanisms, a principle problem is how to represent these machines. There is no specific guideline to sufficiently describe machine schematics. The method of representing varied serial mechanism in a generic format, for the purpose of drawing information about the machine from this configuration file, in order to achieve kinematic simulation of its axes has been developed, which resolves the above mentioned problem. The generic format allows the user to change the input data as per the requirements, thus making it simple and more user friendly. Since this file is written by the user, the simulation can be customized, thus making the tool more flexible.

Machine simulation is used as an approach to validate additive manufacturing tool paths. Integration of this tool with deposition simulation in order to pre-check tool paths with generic approach, has been depicted in the paper and any kind of tool path for a CNC machine can be encoded in this format, thus making it a simple validation tool for layered manufacturing. This aids in saving time and cost. It also helps in collision detection.

In the software-based deposition or simulation system, it is difficult to identify the tasks' temporal attributes, such as execution time. However, this algorithm considers time characteristics of hybrid tasks and links it to the frame rate. The use of the same interface for different machines simplifies user's training and reduces the costs.

Currently, the simulator provides preliminary results that can be used to estimate the errors graphically. [11] Future work that can be done to improve this simulator further is as follows:

- To devise a method for generic representation of parallel mechanisms. This is slightly complicated as the end effector may have n degrees of freedom and is connected to the base by n independent kinematic chains. For example, a hexapod

- Collision detection as shown in Figure 16, that is, detecting the intersection of two or more objects in space by change of color of the two objects.
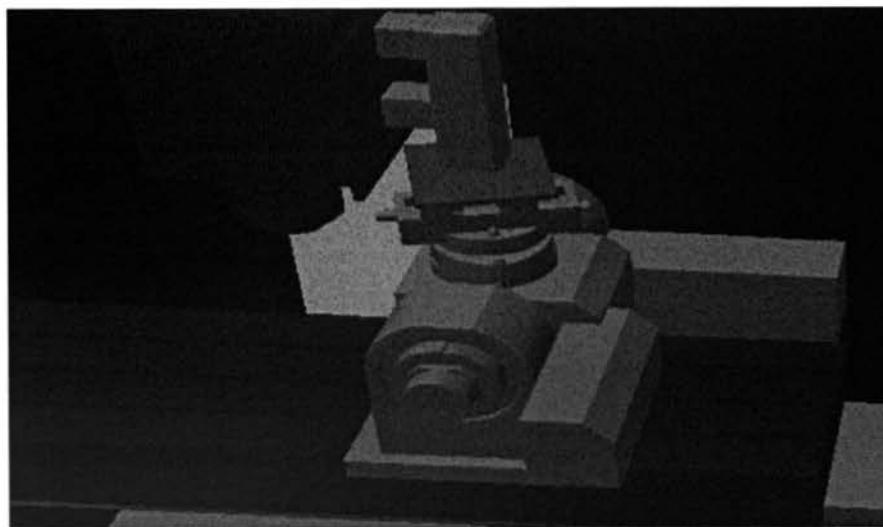

Figure 16. Illustration of Collision of Tool into the Product

17. ACKNOWLEDGMENT

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2. CONCLUSION

A tool that can be used to kinematically simulate varied serial mechanisms as well as validate varied deposition tool paths for CNC machines has been developed. The difference that underlies this approach is the style in which the machine is being represented. A method of representing varied serial mechanism in a generic format, for the purpose of drawing information about the machine from this configuration file, in order to achieve kinematic simulation of its axes has been depicted. Integration of this tool with deposition simulation in order to pre-check tool paths with generic approach has been presented in the paper.

VITA

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