01 Jan 1993

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Recommended Citation

T. C. Chou and F. W. Liou, "Computer Simulation Of Three-dimensional Mechanical Assemblies: Part II - Computer Simulation," *ASME 1993 International Computers in Engineering Conference and Exposition, CIE 1993*, pp. 589 - 596, American Society of Mechanical Engineers, Jan 1993.
The definitive version is available at https://doi.org/10.1115/CIE1993-0071

Computers in Engineering – 1993
ASME 1993

COMPUTER SIMULATION OF THREE-DIMENSIONAL MECHANICAL ASSEMBLIES: PART II – COMPUTER SIMULATION

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ABSTRACT

Computer simulation of the kinematic and dynamic behaviors of mechanical assemblies has become a very important tool in design and manufacturing, because the designer can foresee how a product is going to perform before the product is actually fabricated. However, up to now, the most current simulation modules are based on analysis from another kinematic or dynamic module by specifying the mating conditions between components, and then displaying the motion on the screen. This computer simulation actually performs similarly to a movie, and can only provide visual checking. The drawback of this simulation approach is that designers are forced to use the available joint models, and may lose their creativity. In part I of this paper, general mathematical modeling of the multi-body system is presented, while part II of this paper, a prototype convex-feature modeling system is presented with which a designer can interactively create an assembly of mechanical components ready for dynamic analysis. It can provide a state-of-the-art technology for real simulation of any mechanical systems, and act as a cost-effective test bed for concepts, final design, and control algorithms.

INTRODUCTION

Presented in this paper is a prototype for a generic simulation environment in the computer so that each machine component will be governed by physical laws, and the other physical conditions, such as friction and gravity force will also be modeled. For example, as shown in Figure 1, after all components of a slider-crank mechanism are modeled in feature form, and positioned in the appropriate locations, the simulation of the motion of this system can then be automated according to the governing physical laws embedded in the system, once an external load is specified. Once engineers have created the individual components, they may wish that the following questions be answered in the simulation procedure:

- Can these components easily be assembled?
- Will the assembled mechanism meet the total accuracy specifications?
- When an external force F is applied to the piston, how will the system react?

The first two questions are related to actual tolerance modeling and the last question is about the actual response of the system. From the past experience and published literature, it seems there are at least six problem areas associated with this research:

PROBLEM 1. Part representation – Before any analysis can be conducted, the best method for part representation has to be defined. Besides geometric information, the non-geometric properties are essential, such as
- surface texture and/or finish,
- material and its condition, and
- mating part(s) or assembly(ies).

PROBLEM 2. Kinematics and dynamics modeling -- Fundamental questions, such as how a three-dimensional product is sliding or rotating on a surface, need efficient and realistic modeling.

PROBLEM 3. Collision/contact -- It is important to define and efficiently model two interference states between two bodies, the state of collision in volume, and a state of contact on faces.

PROBLEM 4. Collision/contact response – When two bodies are detected to collide/contact to each other, to realistically and automatically animate the response is an essential task.

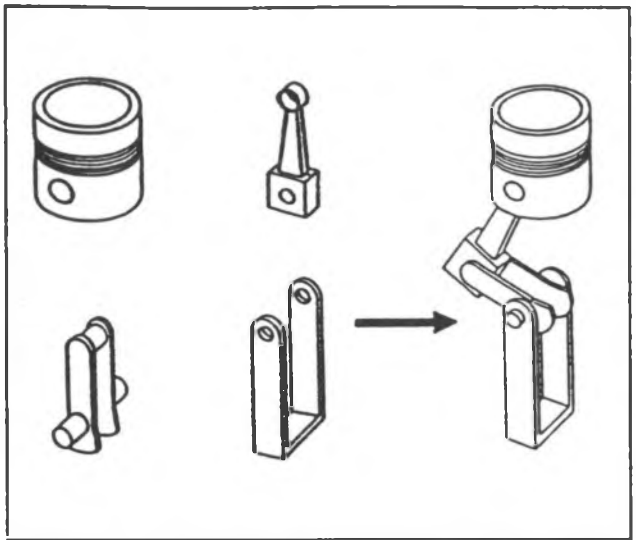

FIGURE 1 A FOUR-COMPONENT SLIDER-CRANK MECHANISM (ROONEY AND STEADMAN, 1987) WILL BE USED AS AN EXAMPLE FOR TESTING

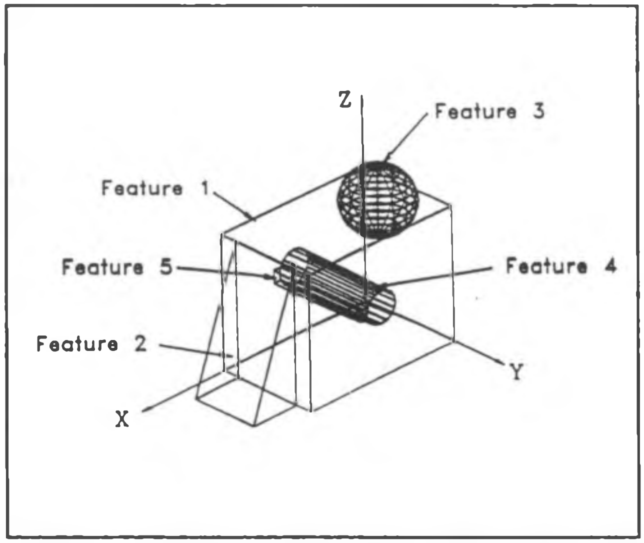

FIGURE 2 WORKPIECE COMPOSED OF FIVE FEATURES

PROBLEM 5. Modeling of multi-body systems – how to efficiently model the constrained motion of a multi-body system is essential in simulating a mechanical assembly.

PROBLEM 6. Animation of 3-D systems -- how to efficiently animate the motion of a 3-D system to provide visual displaying of the problem is also important.

The above six major issues are involved in this realistic simulation system. Part I of this paper has discussed the mathematical formulations to solve problems 2 to 5. Part II of the paper is to address the rest of the issues: part modeling and computer simulation.

FEATURE-BASED MODELING

In order to simulate the dynamics of mechanical assemblies, it is essential to first define a mechanical assembly's initial topology, state of the system and complete definition of the assembly's boundaries. Some geometric information, such as the surface finish, and the material of each part, is also essential to the modeling. A feature-based approach to model mechanical assemblies is used to accomplish the above missions.

A feature-based system normally contains certain primitives or entities such as points, lines, arcs, circles, polygons, free forms, or a higher level groupings of these. The key steps from a CAD description of a workpiece to a finished product include feature extraction and feature-based process planning.

Figure 2 displays an example workpiece which is composed of five elementary features. Using a compact taxonomy, one can set up an accessory feature library to include the possible geometric shapes for mechanical assembly. These features are classified on the basis of topological difference or physical activity. Using a compact taxonomy, one can set up an accessory feature library exhausting most of the possible geometric shapes and specific operations for the usage of mechanical assembly.

Basically, most of the elementary features are simple, symmetric, representative and logical geometries which have distinct attributes. For example, in the case of the rectangular cubic, six faces are perpendicular to each other and the opposite four edges are of the same length. A cylinder has a bar-like shape and two equal-area circles at opposite ends. The similar characterizing attributes of elementary features can be concluded systematically and subjectively, then be emerged into the knowledge base of ideal system.

To generate the part representation into the appropriate feature format, an alternative interpreter which can translate the existing CAD design data into the desired format or a feature-based solid modeler with which the designer can build an object immediately recognizable by the manufacturing planner is necessary.

Since a part is generally composed of many elementary features, the final shape of a part is determined by all the parameters assigned to each elementary feature. These parameters include dimensions, insert point location, rotation angles, concrete or void flag, surface property, and other specifications related to a part's characteristics. For interpreting the parts, an auxiliary (local) coordinate system is introduced to help orientate each feature. In Figure 3, a wedge feature is defined through its auxiliary coordinates and corresponding parameters. Table 1 lists the detailed parameters of features constituting the part in Figure

TABLE 1 LIST OF FEATURES COMPOSING THE PART IN FIGURE 2.

FEATURE NO.	DIMENSION	INSERTION POINT	ROTATION ANGLE	VOID	OTHER*
1. CUBE	5.0, 3.0, 4.0	0.0, 0.0, 0.0	0.0, 0.0, 0.0	NO	
2. WEDGE	1.0, 2.0, 4.0	5.0, 0.5, 0.0	0.0, 0.0, 0.0	NO	
3. SPHERE	1.0	1.0, 1.5, 4.0	0.0, 0.0, 0.0	NO	
4. CYLINDER	0.5, 3.0	2.5, 0.0, 2.0	0.0, 0.0, 0.0	YES	
5. SLOT	0.36, 0.15, 3.0	3.15, 0.0, 1.82	0.0, 0.0, 0.0	YES	

* "OTHER" CAN BE ANY KIND OF ADDITIONAL INFORMATION SUCH AS TOLERANCE, SURFACE PROPERTY, MATERIAL PROPERTY, ETC.

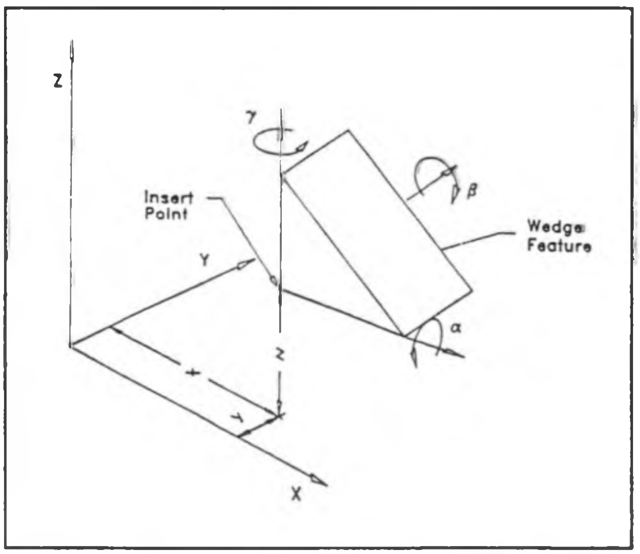

FIGURE 3 FEATURE PARAMETERS DEFINED IN LOCAL COORDINATES

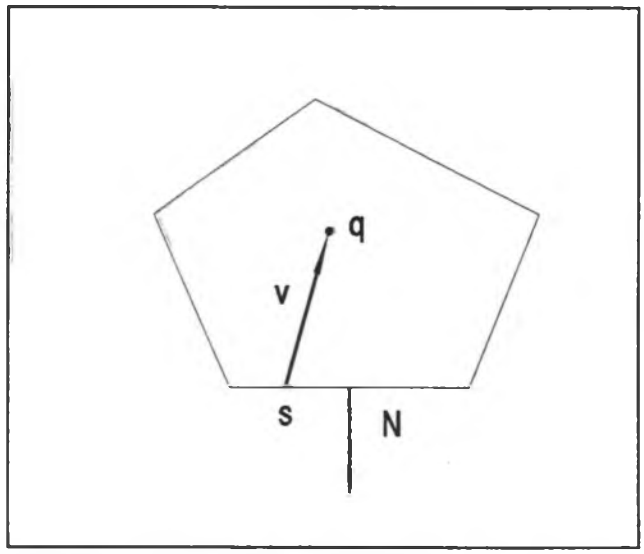

FIGURE 4 COLLISION DETECTING VECTORS FOR CONVEX POLYHEDRA. WHEN A POINT ON THE OTHER FEATURE IS FOUND INSIDE A POLYHEDRA, IT INDICATES A COLLISION OCCURS.

2. An insertion point is the origin of the local coordinate system of a feature. The rotation angles refer to the relative rotational angle between the local coordinate system and the global coordinate system. Adding a "void" flag to the workpiece means to subtract the corresponding volume from a workpiece.

COLLISION DETECTION USING ASSEMBLY FEATURES

There are many different definitions for features. In engineering applications, features refer to a subset of geometry on an engineering part which has a special design or manufacturing characteristics. As a result, feature-based design means a design with features. Based on the geometry, features can be classified by several different ways. For example, face feature is defined by two or three dimensional faces, like hole, gear, fillet, etc., and volumetric features are defined by three dimensional enclosed volumes, such as pocket, slot, keyway, etc.

In this research, features related to assembly are used to model machine components. To develop a reliable collision detection algorithm, it is necessary to find a reliable technique for determining whether a point on a line is inside , on, or outside a

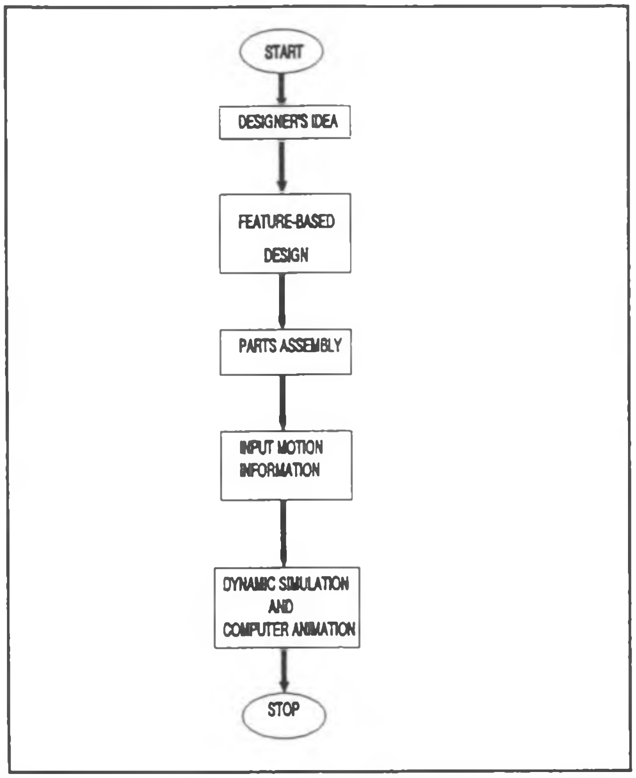

FIGURE 5 FLOW CHART OF THE SIMULATION SYSTEM

feature. This can be accomplished using the two-dimensional Cyrus-Beck algorithm [Rogers, 1985] while the normal vector approach is utilized. This algorithm can tell whether a point is inside a convex polygon, as shown in Figure 4. Point **q** in the figure represents any point on the other feature. If this point is found inside the convex polygon, then a collision occurs. The algorithm takes the dot product of each side's outward normal vector (**N**) with a vector (**V**) from some point on the side to the point in question (**q**).

If **N** • **V** $<$ 0, then the point is inside the convex polygon; otherwise it is outside.

Where **N** represents each side's outward normal vector, **V** represents a vector from some point s on the side to the point in question q. In three dimensional features, the clipping region will be a 3-D convex volume, and all vectors will have x, y, z components.

In calculating for collision detection, only convex features are used, and a concave machine component will be composed into collections of these convex sub-features. Collision of the objects can be detected by analyzing all features composing the objects. In this way, the shape of the machine components can be very general, and the computing speed can be accelerated.

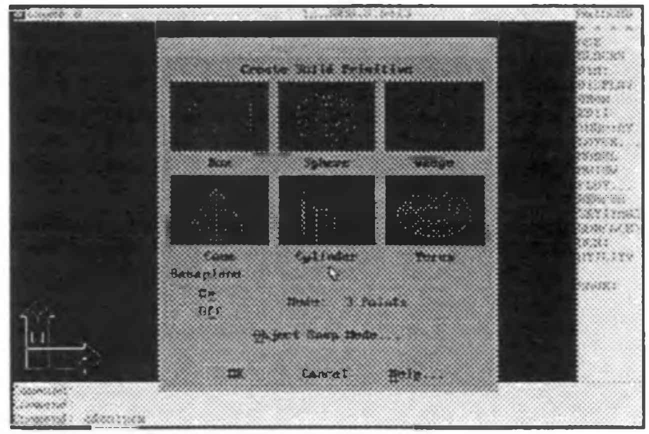

FIGURE 6 AUTOCAD SOLID PRIMITIVES

SOFTWARE SYSTEM

To implement the above mentioned simulation system, the following software features are desired:

- 3D solid modeling capability
- high quality rendering and shading capability
- CSG and/or B-rep information should be obtainable
- open architecture
- high-speed animation capability
- user friendly
- reasonable cost

Unfortunately there are not too many commercial software meeting all the above features. For initial testing, AutoCAD release 12 is used as a tool on PC 486. The AutoCAD Advanced Modeling Extension Release 2.1(AME R2.1) is both a region and solid modeling program. The user can define the physical and material properties of a solid or region, thus allowing the analysis of the object. Autolisp and C are used to develop the codes for the dynamic analysis and graphical simulation. The flow chart of the simulation system is shown in Figure 5. There are six primitives: box, cylinder, torus, wedge, sphere, and cone in AutoCAD AME as shown in Figure 6. The user may use these primitives and combine Autolisp or C to build other features.

CASE STUDY

Feature-based System

A prototype assembly feature library is developed to model machine components. This library is established using Autolisp to do boolean operations on the six primitives in AutoCAD. For example, Figure 7 shows the library of chamfer, fillet, pocket, through hole, blind hole, counterbore, countersink, step, open slot, and blind slot, etc. These features are ready to be used for modeling, as long as the user specifies the dimension,location,and orientation of these features. Figure 8 shows a set of four parts

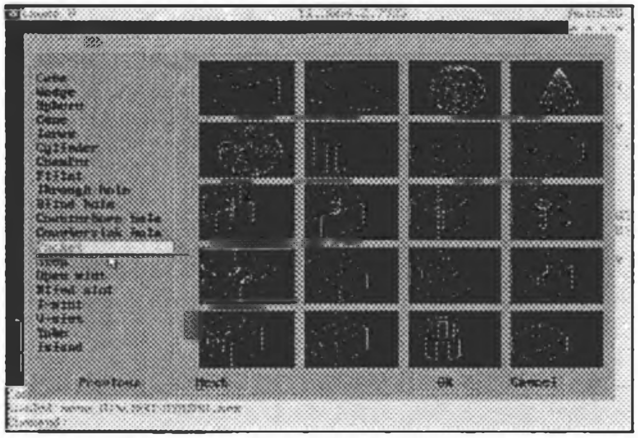

FIGURE 7 3D FEATURE ICON MENU

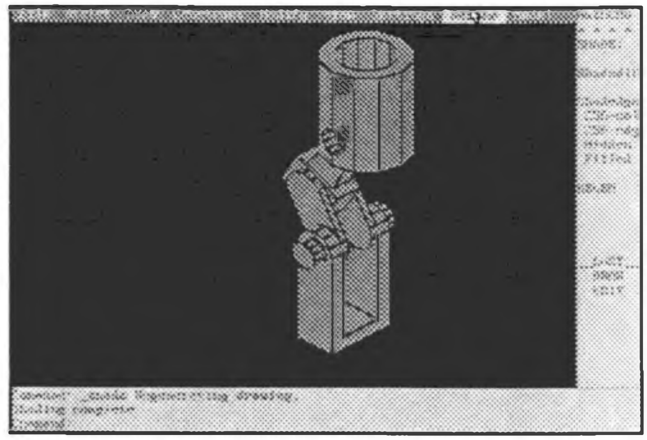

FIGURE 9 ASSEMBLY FIGURE OF PISTON

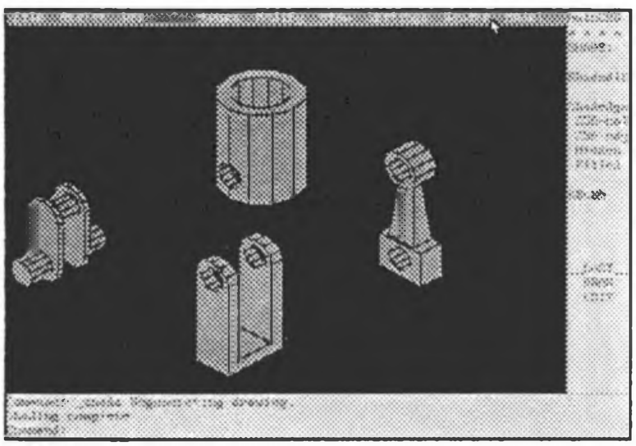

FIGURE 8 A SUBSET OF PARTS MODELED IN AUTOCAD

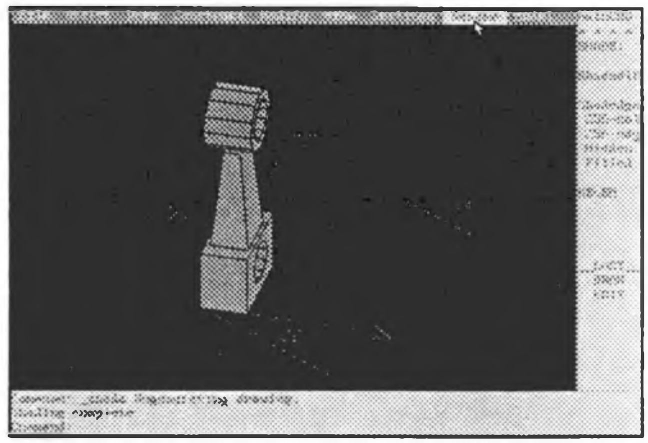

FIGURE 10 THE TRANSFORMED ORIENTATION OF THE CONNECTING ROD

of a slider crank mechanism (piston) modeled by picking up the features from the 3D feature icon menu of this library. After constructing each part, the assembly can be put together by assembling them one by one, as shown in Figure 9.

Dynamic Modeling

For illustration purpose, one of the three-dimensional parts (the connecting rod of the piston) shown in Figure 8 is used as an example. Assuming that this connecting rod is placed on a moving conveyor in an automated assembly line. The dynamic behavior of this rod is simulated when the conveyor is subjected to an acceleration. The dynamic modeling of the system are summarized as follows:

1. Geometric Information: Calculate the centroid and the moment of inertia of each part using AutoCAD AME mass property function.

2. Dynamic Analysis: Using Newton's mechanics and numerical methods to find the relationships between the time and motion using the following relations: As shown in Figure 10,the rod will be in at least one of the following dynamic conditions:

a. Still: If the friction force is greater than the inertia force of the rod,i.e.,

$$F = m a_c < \mu_s W \qquad (1)$$

where m is the mass of the rod, a_c is the acceleration of the conveyor, μ_s is the static friction coefficient between the rod and conveyor, W is the weight of the rod. In this case, the rod will be moving along with the conveyor.

b. Impending: If the inertia force of the rod is equal to the maximum friction force between the rod and the conveyor,i.e.,

$$F = ma_c = \mu_s W \quad (2)$$

then the rod is in an impending condition. i.e., the rod will be maintaining its initial condition.

c. Sliding: If the friction force is less than inertia force,i.e.,

$$F = ma_c > \mu_s W \quad (3)$$

then the rod will be sliding along the conveyor.

d. Rotating: As shown in Figure 10, applying Newton's second law, and assuming Y_c is the distance from Y axis to centroid, X_c is the distance from X axis to centroid, Z_c is the distance from Z axis to centroid, θ is the orientation angle of the insertion point, and μ is the kinematic friction coefficient, by taking moment with respect to X axis, one can find that when rotation occurs,

$$\mu = \frac{Y_c}{Z_c \cos\theta} \quad (4)$$

If $\mu > \mu_s$, it will be impossible for rod to rotate with respect to X axis. Similarly, by taking moment with respect to Y axis, we obtain

$$\mu = \frac{X_c}{Z_c \sin\theta} \quad (5)$$

If $\mu > \mu_s$, it will be impossible for rod to rotate with respect to Y axis.

Suppose it rotates with respect to X axis, taking moment with respect to centroid, the following equation can be obtained:

$$I\alpha = W(Z_c \mu \cos\theta - Y_c) \quad (6)$$

where I is the moment of inertia of the rod respect to centroid, α is the angular acceleration of the rod in rotating. This equation can then be used to find the angular acceleration of the rod during rotation. Numerical integration can be performed to find its angular velocity and angular displacement.

3. Computer Simulation: Use Autolisp to generate and display the pictures to present the locations and orientations of different parts according to the dynamic analysis result.

Computer Simulation of a Piston Connecting Rod.

From the example that the connecting rod is placed on a moving conveyor in an automated assembly line. The dynamic behavior of this rod is simulated when the conveyor is subjected to an acceleration. The gravity force and the friction force between the surfaces are automatically modeled in the system. The magnitudes of the applied conveyor velocity and acceleration, and the position and orientation of the rod can be defined by the user. Based on the above information, the computer can automatically generate the dynamic conditions of the rod: still, sliding, and/or rotating. Figure 11 to Figure 18 show a sequence of the simulated rotating rod on the computer.

CONCLUSION

This set of papers outline a new approach to automatically simulate 3-D mechanical components. Full development of this research can provide a technique for real simulation of general mechanical assemblies. It can act as a cost-effective test bed for concepts, final design, and control algorithms. As computers become less expensive and more powerful, this simulation approach will be even more useful. The result of this research will have strong impact in several major areas. Some examples are illustrated as follows:

1. Development of new product assemblies: As newly designed mechanical assemblies can fully be tested in the real simulation environment, product development cycle time, product reliability, and product quality can be greatly improved.

2. Planning of flexible fixturing process: Because properly fixturing a workpiece is a bottleneck in manufacturing of products with small batch sizes, fixture planning has become a key issue in flexible manufacturing systems. However, this is also a labor-intensive task. The adoption of the proposed approach can simulate whether a workpiece is properly fixtured, and therefore, the complete fixturing plan can be implemented in a CAD system.

3. Development of control algorithms: Since the complete dynamic behavior of a mechanical system can be simulated in the CAD system, the development of control algorithms for complex mechanical systems can be tested in advance. This will provide a cost-effective and efficient simulation environment.

ACKNOWLEDGEMENT

The authors would like to express their appreciation for the support from the National Science Foundation under Grant No. DDM-9210839.

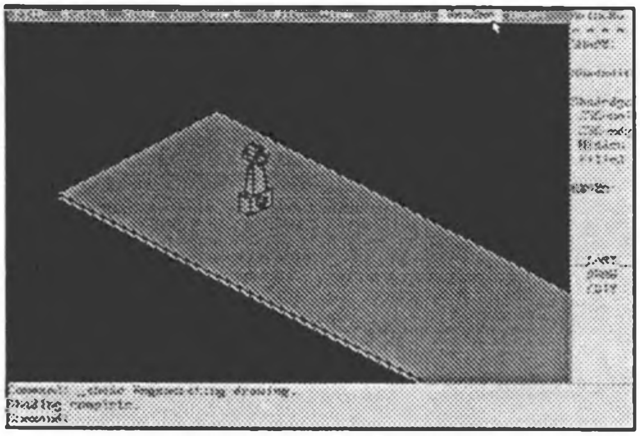

FIGURE 11 T = 0.01 SEC

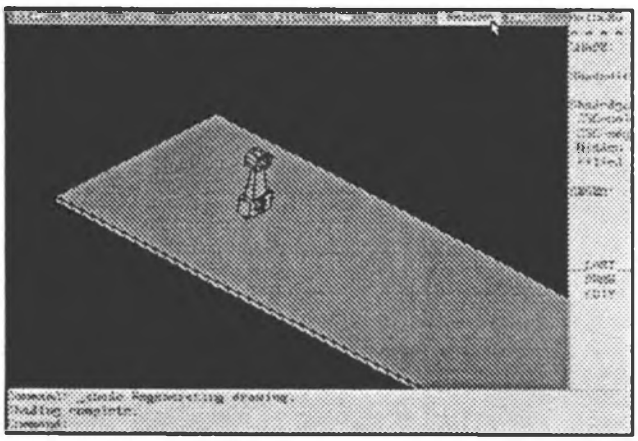

FIGURE 12 T = 0.03 SEC

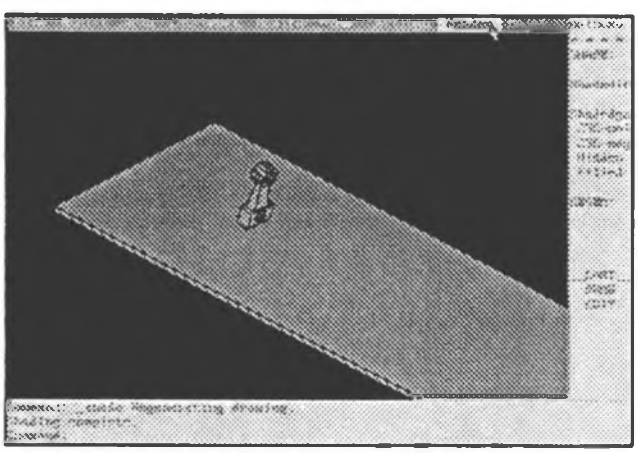

FIGURE 13 T = 0.05 SEC

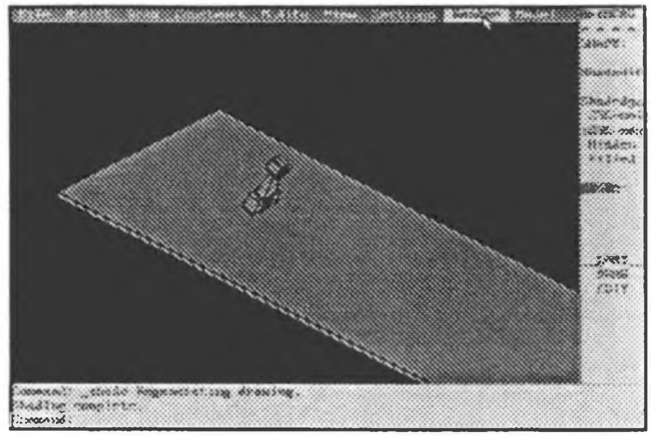

FIGURE 14 T = 0.07 SEC

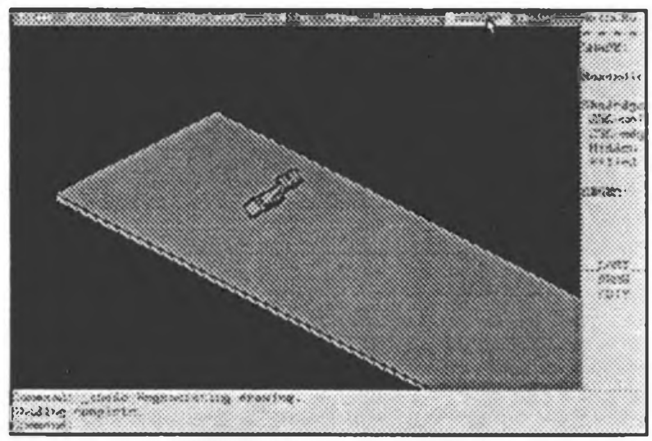

FIGURE 15 T = 0.09 SEC

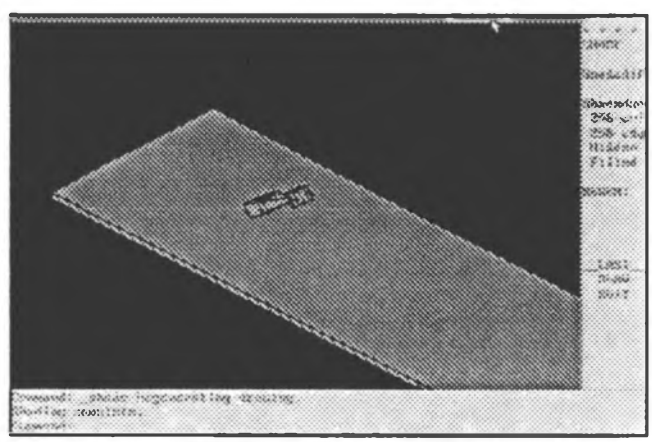

FIGURE 16 T = 0.11 SEC

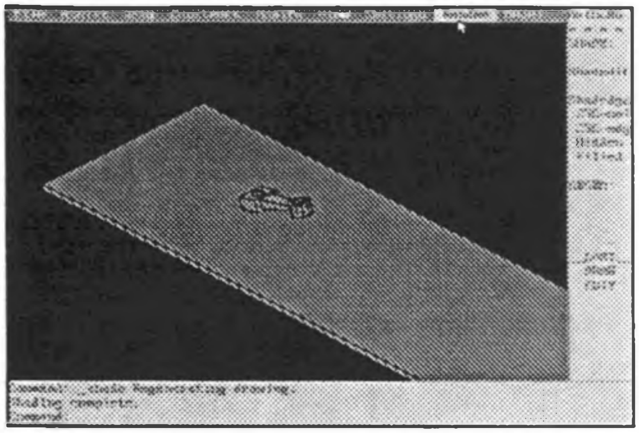

FIGURE 17 T = 0.13 SEC

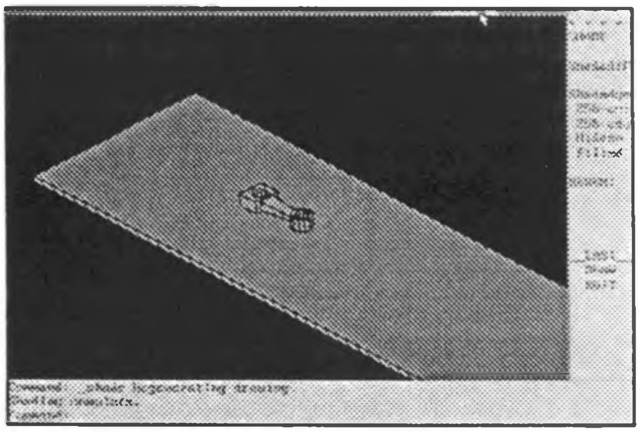

FIGURE 18 T = 0.15 SEC

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