A Dynamic Behavior Modeler for Future Inclusion into a Multi-Tasking Motion Planning System for Material Handling in Construction

By

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(ABSTRACT)

Construction has multiple material handling equipment that cross each others' paths. These equipments have significant dynamic behavior under various load conditions. A system to model multi-tasking material handling with dynamic behavior capabilities will provide advances in automation.

Current computer graphics and CAD technology, combined with advanced engineering concepts provide the capability for a dynamic behavior modeler which is capable of modeling the dynamics of mechanisms involved in the material handling operations in construction realistically.

This thesis presents a conceptual dynamic behavior modeler. The conceptual modeler is envisioned for future inclusion into a multi-tasking motion planning system for material handling in construction. The conceptual modeler is intended to perform dynamic simulation of 3-D rigid bodies for computer animation. In addition, the modeler provides a capability to model and predict real-life behavior of physical objects subject to dynamic loading.

This thesis also presents a sample animation case involving a mobile crane in a "pick and place task". Although traditional animation methods have been employed for the sample case, the animation provides an insight to the realistic visualization that would be achieved through dynamic simulation. In order to achieve a real-time animation, no finite element modeler has been utilized. Also, significant work was done to study approximation strategies in the development of the analytical model of the sample case to improve the efficiency of the animation.

The dynamic behavior modeler presented in this thesis will provide a novel approach to model the motion planning process. The modeler will ensure realistic visualization of material handling operations. The modeler will allow engineers to animate the material handling process based on dynamic simulation. Engineers will be able to realistically model critical rigging operations. The technology provided by the dynamic behavior modeler will enable engineers to better plan, model, and control the material handling process. This will further lead to significant improvements in constructability and overall performance of construction projects.

ACKNOWLEDGEMENTS

I am very fortunate to have had Dr. Yvan Beliveau as an advisor. His continual guidance, support and friendship provided an invaluable catalyst during the course of this research and thesis. He significantly contributed to the quality of this thesis. In fact, his contributions to my education are not limited with this thesis. The new ideas and technologies that he introduced to me have reshaped and broadened my view of construction engineering and management. Dr. Sankar Jayaram's contributions were of significant aid throughout this research and thesis. His knowledge of CAD technology and his superb teaching skills significantly assisted me to understand and work on the technical aspects of this thesis. Dr. Thomas Murray also contributed to the quality of this thesis with his constructive comments. I thank my advisory committee for their contributions to my education and their willingness to review my thesis.

I would like to thank Shrikant Dixit for his assistance in coding the sample animation program. Without his help, "the funny looking thing" would have never been moving. I would also like to thank Raul Andruet for his assistance in developing the analytical model of the sample case.

I would like to find a "word" that can express my gratitude and love for my parents Necati and Lamia Dal without whom this thesis would have never been written. They have always been encouraging and supporting throughout my graduate education. Finally, I would like to dedicate this thesis to my mother, Lamia Dal. I know how deeply she has suffered from being away from her "biricik" son.

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CHAPTER 1

INTRODUCTION

Technological improvements have made new ideas in engineering possible which were not previously envisioned. As technology reaches new dimensions, the major stages of engineering (i.e., planning, designing, etc.) are afforded significant benefit.

Parallel to the continuous developments in technology, various engineering disciplines have been driven to interact with each other more closely. For example, the enhancements in CAD hardware achieved by computing specialists are utilized by mechanical engineering to speed up the design process; the automation applications developed by several disciplines within engineering are utilized by civil engineers to improve the productivity of construction projects. The close interaction among various engineering disciplines provides tools, methods, concepts, etc. to reach objectives faster and obtain better results in terms of quality, functionality, cost and reliability.

Over the recent past, automation of the engineering process has become a major focus. Increased availability and decreasing costs of CAD/CAE tools have resulted in significant improvements in automating several distinct stages of the engineering process (Cleveland 1989; Hendrickson and Maher 1989; Baecher et al. 1989).

Construction engineering stands as a field that has significant potential for integration of various engineering technologies. There is an increasing need to improve 'constructability'. This need has led the parties involved in the construction industry to seek remedies in advanced technological concepts and tools. One of the remedies has been the implementation of automation concepts and tools to construction projects.

Material handling has a critical impact on the successful completion of construction projects; and material handling is an operation that has potential for automation. Partial and full automation of mobile construction equipment such as trucks; excavating and grading equipment such as scrapers, loaders, compactors; material hoisting equipment such as cranes, forklifts is possible (Paulson 1985).

Efficient transportation of physical objects is an important task in construction and manufacturing. Efficient transportation has experienced significant advancements for the manufacturing. Off-line programming systems have been used in manufacturing to improve transportation efficiency. However, these systems are not capable of handling large deflections and vibrations of the manipulating equipment and objects found in construction. Therefore these systems have limited applications for the construction process.

The capability to predict real-life behavior of physical objects and equipment provides significant enhancements for automation of the material handling process. Computer animation of such a process based on dynamic simulation provides an excellent tool for planning material handling operations.

It is believed that the current Computer Graphics and CAD technology, combined with engineering expertise can provide the technology necessary to achieve a dynamic behavior modeler capable of realistically modeling the dynamics of mechanisms involved in the material handling operations.

This thesis presents a dynamic behavior modeler for future inclusion into a Multi-Tasking Motion Planning (MTMP) system for material handling in construction. The major focus of this thesis is the research and work done to develop the conceptual aspects of such a dynamic behavior modeler. The current research does not provide the implementation of the full MTMP system, since significant effort of many man-years is required for such an implementation. However, an overview of the MTMP system will be presented.

The dynamic behavior modeler introduced by this thesis is intended to perform dynamic simulation for computer animation. Modeling and simulating dynamic behavior is an essential component to achieve a good visualization of real-life performance in the construction environment.

Future implementation of the dynamic behavior modeler will be performed in WALKTHRU™, which will be the platform for the development of the MTMP system. WALKTHRU is a 3-D animation software developed by Bechtel Software, Inc. Section 1.5 describes the WALKTHRU system in more detail.

The development of the dynamic behavior modeler heavily relies on incorporating integral properties (mass properties) of solids into WALKTHRU. In order to plan or control static or dynamic behavior of objects in CAD applications, it is necessary to evaluate integral properties of solids (e.g., volume, center of gravity, mass moments of inertia, etc.). The incorporation of these properties enables the use of the physical quantities (e.g., inertial forces, torques, elastic behaviors, etc.) in addition to geometry to better model and control the environment. The integral properties of solids issue will be discussed later in the thesis.

Section 1.1 below presents the motivation behind this thesis and research. Following this, the subsequent sections will provide a look at the thesis objectives, scope and limitations, methodology of the thesis, and computer technology utilized within the research. Finally, Section 1.6 will outline the contents of the thesis.

1.1 Motivation

Construction has multiple material handling equipment (cranes, loaders, lifters, etc.) that cross each others' paths. These material handling equipment have significant dynamic behavior under various load conditions. If advances in automation for the construction industry are to occur, a system to model multi-tasking material handling with dynamic behavior is required.

No efficient tool has been developed which can effectively model a multi-tasking system with more than two material handling components. The construction industry has many material handling operations all performing concurrently.

The MTMP system for material handling will seek to better plan, model and control multi-tasking operations, and provide a unique tool for the construction industry. The ability to better plan multi-tasking material handling lies at the heart of reaching feasible, reliable and safe working environments. The ability to plan the construction sequence will be of significance. Given the technology, continuous simulation of the processes will identify areas of conflict, potential delays, methods to alert for critical safety conditions, and an overall planning environment currently unavailable (Beliveau et al. 1991).

As mentioned before, the development of a dynamic behavior modeler is an essential component for the MTMP system. To achieve reliable material handling automation, the inclusion of such a modeler into the MTMP system is necessary. There are several issues stated below, which motivated the development of the dynamic modeler.

One of these issues, as revealed by literature review, is that currently there is a significant need to have a dynamic behavior modeling capability to perform dynamic simulation of mechanisms such as cranes and robots involved in material handling operations. This capability is a must to animate the operations with a satisfactory degree of realism, leading to reliable visualization.

Another issue is the availability of the technology required to develop the capability mentioned above. It is possible to model construction environments with available CAD technology. It is also possible to compute and store mass properties for all objects in these environments. A provision can be made to describe relationships between objects and the constraints for manipulating mechanisms. This defines the degrees of freedom for each object and also the constraints on motion in each degree of freedom. The integral properties of objects, combined with applied mechanics, enable the prediction of the physical behavior of these objects. Hence; for a particular object, the effects of inertial forces can be computed; and deformations due to torques, bending, swaying, etc. can be obtained. If the external forces are present, the deformations due to these forces can also be computed. For planning a particular process, deformation of all relevant objects can be recorded. These deformations can be simulated. Interference detection capabilities built into the simulation system can predict collision between objects. All of the above is replayed as a time based animation of the real-life behavior of the given system.

In addition to the realistic visualization provided through a dynamic behavior modeler, a reliable and simplified modeling technology can be achieved by the incorporation of such a modeler into a generic data model. A generic data model can serve as a basis for integrating CAD/CAE and visualization systems. With a dynamic behavior modeling capability, such a data model can be utilized for dynamic system modeling, dynamic simulation, and graphical animation.

As a final motivation, the inclusion of the dynamic behavior modeler into the MTMP system will ensure proper and safe planing of a multi-rigging multi-tasking environment. The following example is taken from a proposal submitted to the National Science Foundation by Beliveau et al.:

1. Introduction

> "The example is the construction/manufacturing process of installing a reactor core into a submarine assembly. No method exists where stresses and strains can be modeled for each component of the material handling process. The forced rotations, tilts, lift, etc. of this process exert potentially dangerous loading conditions. Currently, there is no way of modeling how an object will roll or swing given the inertial forces. There is a need to simulate a feasible solution while maintaining safe tolerances. The direct output of control information can serve to provide user augmented control and with limited real-time sensing a significantly improved multi-rigging planning process will be provided. The inclusion of a real-time interactive finite element modeler into the MTMP system should be a future advance to this system" (Beliveau et al., 1991).

The proposed MTMP system will provide a basis for automation of the construction industry. The proposed system will improve planning and safety within the construction industry. It will also provide a novel approach to planning complex robotics systems.

As stated before, the dynamic behavior modeler is an essential component of the MTMP system. Thus, the modeler will contribute significantly to all the improvements achieved through MTMP. Major contribution is expected to be the high level of realism which will be introduced to visualization and simulation of the material handling operations. Certainly, this will lead to better planning, designing, and control of operations. Hence, significant improvements in performance (e.g., productivity, safety, quality, timeliness, etc.), and in constructability (e.g., reduce in rework and accidents, etc.) can be expected throughout the construction projects involving material handling operations.

1. Introduction

1.2 Thesis Objectives

The thesis seeks to develop a conceptual model of a dynamic behavior modeler which can be included at a future date into a multi-tasking motion planning system for material handling in construction. To accomplish this objective, the research aims to establish the technology necessary to incorporate the integral properties of solids into WALKTHRU. In addition to this, the research aims to identify the strategies required to achieve a dynamic simulation capability for computer animation. Such a capability is essential in order to generate a data model to integrate WALKTHRU with CAD/CAE systems. The realization of these goals will extend WALKTHRU from a visualization tool to an enhanced animation and simulation package with analysis and design capabilities. Hence, these capabilities will provide a tool which help significantly in modeling and planning material handling effectively, and in evaluating the design performance of mechanisms .

The thesis will also introduce the Multi-Tasking Motion Planning system. MTMP is a system envisioned per a proposal to the National Science Foundation. The conceptual and theoretical aspects of the system are presented. The capabilities of the system are believed to be able to justify the system's significance for automation of a reliable and efficient material handling process in construction.

1.3 Scope & Limitations

This research is partially funded by Bechtel Software, Inc. to provide WALKTHRU with analysis and design capabilities. In that context, the scope of this thesis is limited to determine the tasks and procedures to model dynamic behavior. The scope is limited to identify the strategies to develop a conceptual model of the dynamic behavior modeler.

The implementation of the dynamic behavior modeler into WALKTHRU is not included in the scope of the thesis due to a significant time period required to modify the restrictions existing in the current version of WALKTHRU. The implementation of the algorithms (writing the code), and the modification of data structures of WALKTHRU to store the required information will be further performed concurrently by other co-researchers. WALKTHRU with the added capabilities will be more robustly tested by Bechtel Corp. However, the algorithm required to incorporate integral properties of solids has been coded and tested as a part of the research. The testing process has yielded good results.

A dynamic model of a load attached to a mobile crane is developed to display the dynamic behavior of the suspended load and the crane's boom. It has been necessary to introduce certain limitations to the prediction of the dynamic response in order to have a manageable problem space and an effective result. Hence, some restrictions are placed on the complexity of mechanisms. Some approximations are also introduced to the mathematics involved to compute the dynamic behavior of the objects. Consequently; several approximations which simplify the problem are used. These approximations are utilized, provided that a good visualization of real-life performance is achieved. The assumptions and approximations are further discussed in Chapter 4.

1.4 Methodology

This section describes the research methodology for various tasks involved in the development of the dynamic behavior modeler.

As stated in section 1.2, the primary objective of this thesis is to identify the theoretical aspects of a dynamic behavior modeler to perform dynamic simulation for computer animation; hence to visualize the real-life behavior of objects in a CAD environment. The attainment of this goal depends on the following tasks which constitute the methodology for the research. Figure 1.1 illustrates the methodology followed for the research.

1- The study and review of the concepts and technologies (e.g., dynamic simulation and animation concepts, dynamic behavior analysis, integral properties of solids, motion planning, etc.) relevant to the tasks involved in the development .

2- The determination and coding of an algorithm to compute integral properties of physical objects from their surface models. This is equivalent to converting hollow 3-D surface models to solid 3-D models.

3- The identification of the strategies to provide WALKTHRU with a modeler to perform dynamic simulation for animation. The theoretical aspects of such a modeler serving for the purpose of realistic visualization are developed.

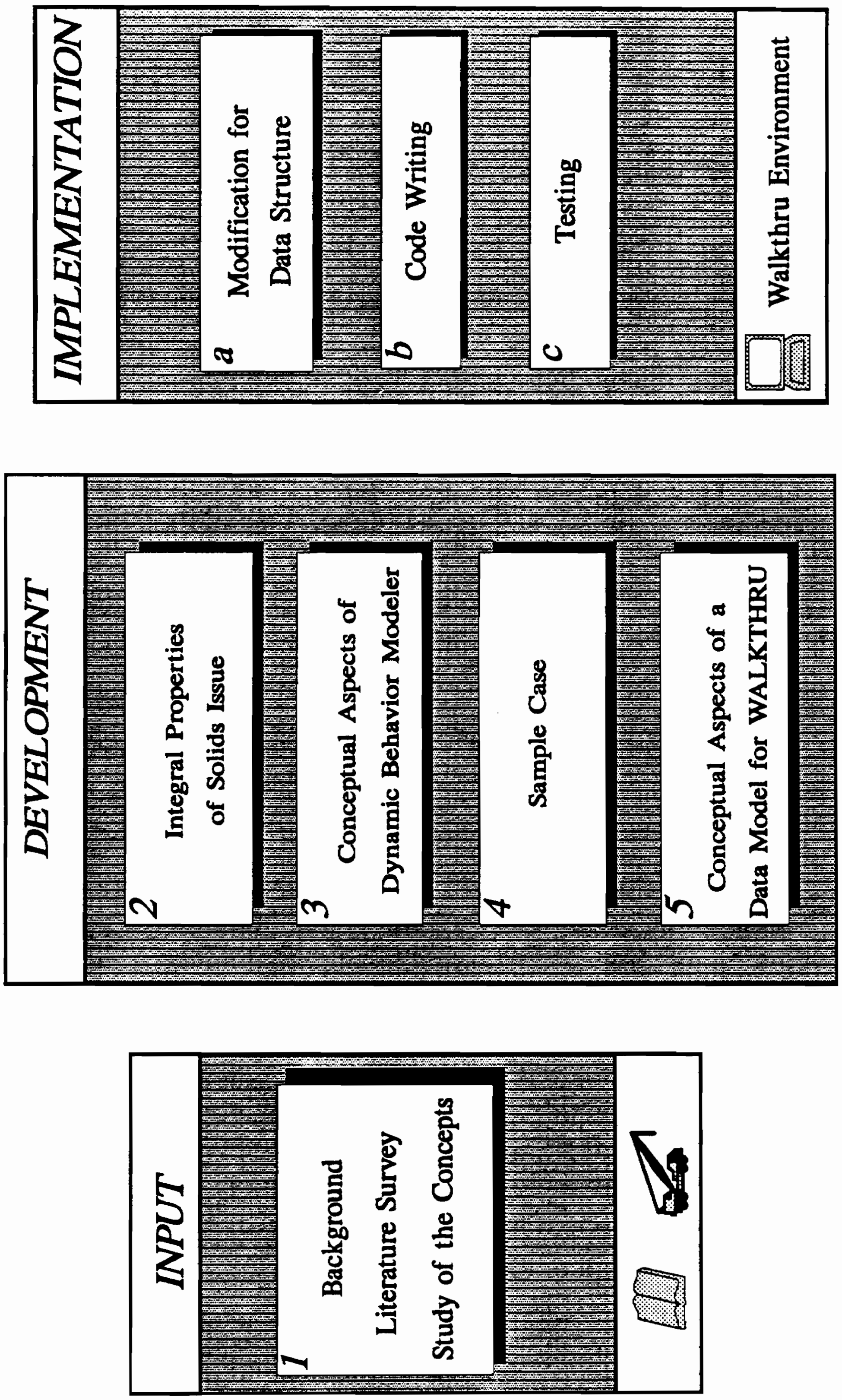


Figure 1.1: Thesis Methodology

4- The development of an analytical model of a load attached to a mobile crane. The dynamic behavior of the suspended load is modeled with respect to different stages involved in a "pick and place task". Based on this analytical model the displacements along the crane's boom can be determined. Both the dynamic behavior of the load and the displacements along the boom are displayed by means of a GL (Graphics Language) program. However, this GL program does not depend on dynamic simulation for computer animation. The animator has all the control. The main purpose of this program is to provide an insight to the visualization that would be achieved by the dynamic behavior modeler to perform dynamic simulation for computer animation.

5- The discussion of an existing generic data model which serves as a basis for integrating CAD/CAE and visualization systems. An extension to the data model through the incorporation of the dynamic behavior modeler is proposed. Such a data model envisioned for WALKTHRU is presented.

As stated earlier, the implementation of the dynamic behavior modeler into WALKTHRU is not included in the scope of this thesis. However, the tasks involved in such an implementation process are given briefly below:

a- Modification of data structures. This task involves creating new data structures to store physical properties, connectivity relationships between objects, kinematic constraints, joint definitions, local coordinate frames, etc. The binary data structure of WALKTHRU has to be modified to attain an ability to update and store new coordinates between keyframes during animation. This is required to achieve dynamic simulation.

b- Writing code. The code writing will be required to implement the behavior functions (e.g., dynamic response of a load to a sudden acceleration, etc.), equations of motion as well as inverse/forward dynamics and kinematics.

c- Testing. Due to the fact that dynamic behavior analysis relies on a considerable degree of approximations, it is required to make experiments to test the results of analytical models. Therefore, experimental data should be provided, and compared with the results obtained from the dynamic behavior modeler.

The above described tasks involved in the implementation process will further be addressed in the thesis.

1.5 Technology Review

WALKTHRU technology serves as the environment where the implementation of the dynamic behavior modeler will be performed. Further, the development of the MTMP system will also take place in the same environment. Therefore, WALKTHRU plays an important role in this research. This section intends to describe WALKTHRU briefly.

WALKTHRU was developed by Bechtel Software, Inc. The WALKTHRU User's Manual (WALKTHRU User's Manual, Version 3.0 1988) describes WALKTHRU as follows:

> "WALKTHRU is a real-time, three-dimensional (3-D) simulation system that allows the user to interact with existing 3-D computer models in a fully lifelike manner. With WALKTHRU and a color graphics workstation, the user moves through the 3-D computer model, seeing the physical objects as they would appear in the real world. WALKTHRU gives the user complete control of his/her body and head orientation as the user moves through the model. Real-time animated images, displayed in color with perspective, provide a lifelike simulation of the user's movements. The user can also control the motion of individual objects in the model."

Simulation is the process of designing a model (mathematical, logical, or geometric) of a real system, and experimenting with the model. Visual simulation (animation) is a specific type of simulation process. Animation is the process of creating the illusion of motion for the designed model on graphics display (Morad et al. 1991).
Besides the above defined capabilities, WALKTHRU has interfaces with several CAD/CAM software (such as CADAM, CATIA, AutoCAD). This capability makes WALKTHRU an excellent tool for modeling the construction environments.

The real-time graphics capability of WALKTHRU provides a lifelike simulation of object motion. WALKTHRU's "Record" function can record any path of motion, as well as the motion of the 3-D objects. The "Replay" function can construct this combined viewer and object motion, resulting in an animated "tour" of the model. The user can replay the motion of the objects, and review the effects of movement through the 3-D computer model while the objects are in motion. Another feature of WALKTHRU is the "Interference Detection" function. While the user moves the objects around, WALKTHRU can check if there are any interferences with other objects in the environment. Interferences are highlighted on the screen.

All the capabilities possessed by WALKTHRU are of significance for the development of the MTMP system. Hence, WALKTHRU provides a good platform to support the proposed MTMP system.

However, some modifications for WALKTHRU, described briefly in Section 1.5, are required for the development of a dynamic behavior modeler. These modifications are believed to extend WALKTHRU from a visualization tool to an enhanced simulation and animation package with design and analysis capabilities. These modifications are discussed in more detail in Chapters 3, 4 and 5.

1.6 Presentation of Thesis

This thesis introduces the theoretical aspects involved in the development of a dynamic behavior modeler to perform dynamic simulation for mechanisms (such as cranes, robots) involved in material handling operations. Such a modeler is an essential component of a multi-tasking motion planning system for material handling in construction. The thesis describes the conceptual model of a dynamic behavior modeler and gives an overview of the MTMP system. The thesis emphasizes the significance of such a system for better planning and automation of material handling operations. The advances in material handling operations will enable the construction industry to significantly improve constructability.

Chapter 2 describes the MTMP system. Two of the three major components of the system; (1) dynamic motion planner, and (2) control and simulation mechanism for robotics and automation are discussed in detail. The significance of the system is presented from both the technical and the application point of view. The emphasis is on the potential improvements in constructability. Significance in applications is supported by possible scenarios.

Chapter 3 stresses the significance of the integral properties of solids issue. The development of a dynamic behavior modeler in a CAD environment heavily relies on the existence of a capability to evaluate these properties. The algorithm to incorporate these properties into WALKTHRU is presented.

Chapter 4 focuses on the dynamic behavior modeler, the third major component of the MTMP system. The literature review and information about current and previous technologies and some concepts are provided. The theoretical aspects and the strategies involved in such a modeler are discussed. Chapter 4 also presents a sample case involving a suspended load transported by a mobile crane. The dynamic behavior of the load and the response of the crane's boom to dynamic loading are analytically modeled. Such a model helps to predict the dynamic behavior of the suspended load throughout a material handling process, and the displacements occurring along the crane's boom. The analytical model is coded for animation purposes through a GL program written in Virginia Tech. However, this animation does not depend on the theoretical aspects which will be discussed in Chapter 4; it is merely for visualization purposes.

Chapter 5 presents a generic data model for rigid body dynamic system modeling, dynamic simulation, and graphical animation. Such a model can provide a basis for integrating CAD/CAE systems and WALKTHRU. The dynamic behavior modeler presented in Chapter 4 is envisioned as a significant component in the data model which is believed to enhance WALKTHRU with a capability to evaluate the design performance of mechanisms.

Chapter 6 is the concluding chapter. A summary of the previous chapters is presented. Recommendations, and future advancements are addressed in this chapter. Also, a conclusion of the work is presented.

Appendix A describes a triangulation algorithm which was developed in Virginia Tech. This triangulation algorithm is required to have efficient results from the algorithm which is to compute integral properties of solids.

Appendix B presents the listing of the algorithm required to incorporate integral properties into WALKTHRU. The listing has been coded in C programming language.

Appendix C presents a brief derivation of the equations of motion. The equations of motion are derived from D'Alembert's principle of virtual work.

Appendix D describes the current "pathfinder" algorithm which will be of significance in the dynamic motion planner component of the MTMP system.

Appendix E presents the derivation of the equations which describe the dynamic behavior of a load attached to a mobile crane, and the response of the crane's boom to the dynamic loading for each stage of a sample case.

Appendix F provides the source code of the GL program written to animate the sample "pick and place" operation. However, this animation is not based on dynamic simulation. It only provides an insight into the visualization that can be achieved through the dynamic behavior modeler.

CHAPTER 2

THE MTMP SYSTEM OVERVIEW

This chapter is an overview of the Multi-Tasking Motion Planning system. The conceptual and theoretical aspects of the MTMP system were developed by the Construction Management and Engineering Division of Virginia Polytechnic Institute and State University, and proposed to National Science Foundation. The proposal is being evaluated for funding by the National Science Foundation when this thesis was being written.

It is well known that there are multiple material handling equipment (such as cranes, forklifts) conflicting with each others' paths in construction. There is a need for a tool which ensures the productive and safe operation of the material handling equipment. Such a tool will contribute significantly to the efforts to improve constructability. The need for a tool to reliably and realistically model the material handling process motivated the proposition of the MTMP system.

The MTMP system is envisioned as a technology which aims to help better plan, model, and control material handling equipment found in construction. It is believed that the

MTMP system will significantly help constructors and designers better plan a multi-task environment for material handling.

The MTMP system will provide a geometric solution to multi-tasking motion planning for material handling in construction. The system will provide a method to effectively plan conflicting multiple material handling operations. MTMP capabilities will play a major role for automation of the construction process. A new method to plan and model motion of autonomous vehicles or robots will be provided. MTMP can further provide a mechanism to directly output code to automate the overall material process. This capability is not currently available. It is expected that the successful conclusion of the system will bring about significant development in automation on material handling (Beliveau et al. 1991).

There are three major tasks involved in the development of the MTMP system: (1) the development of a 3-D dynamic behavior modeler, (2) the development of a dynamic motion planner, and (3) simulation and control for automation. These areas require differing technologies and capabilities. The development of the dynamic behavior is the subject of this research and thesis, and relies on incorporating physical properties into the motion planning process. The dynamic motion planner provides a geometric solution rather than a mathematical solution to a multi-tasking motion planning process. The simulation and control for automation utilizes a simulation system to model the environment and directly output control code for the multi-tasking automation process (Beliveau et al. 1991).

Figure 2.1 (Beliveau et al. 1991), Data Flow for the MTMP System, taken from the proposal submitted to the National Science Foundation gives an overview of the system. The upper left quadrant represents the 3-D dynamic behavior modeler presented by this

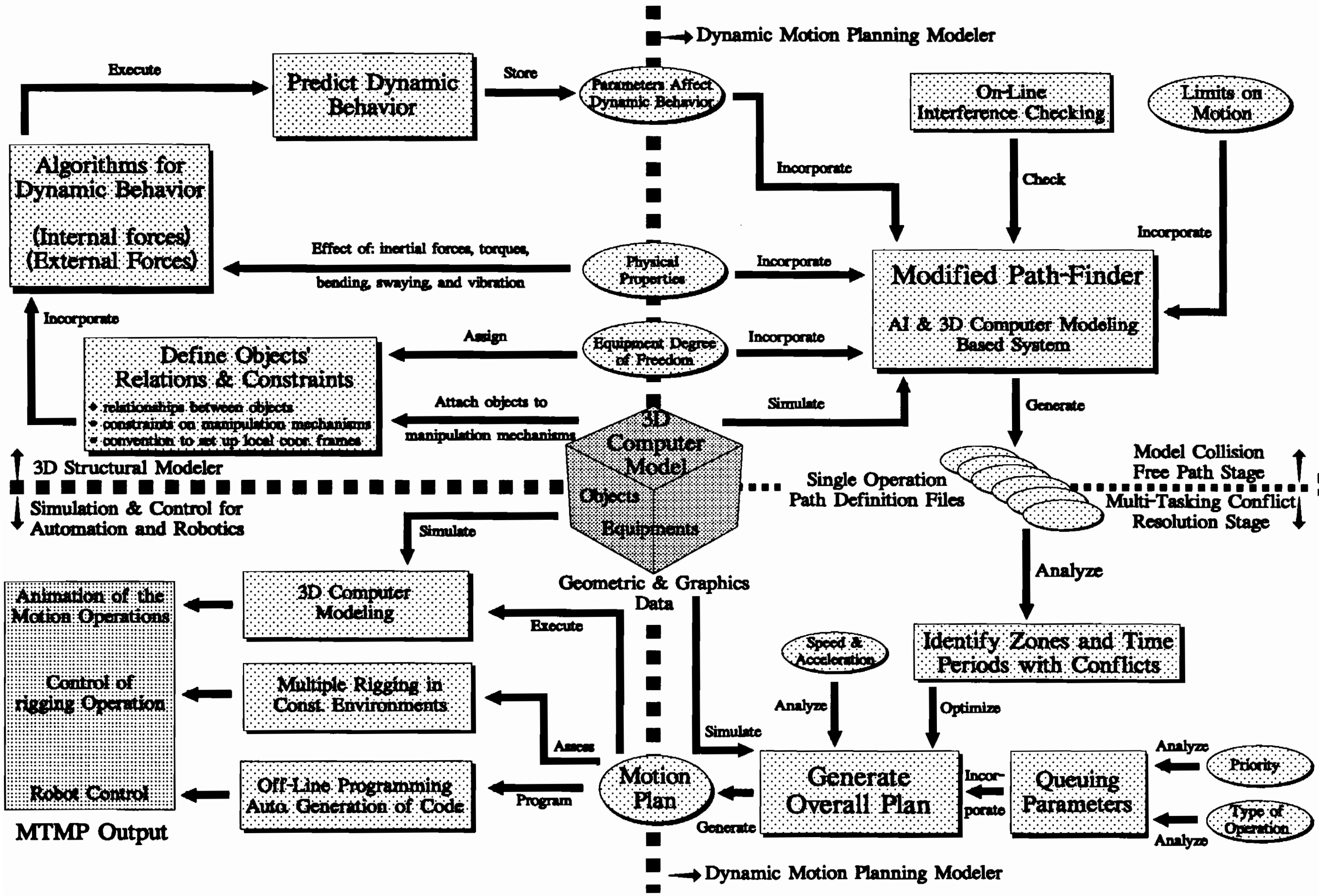

Dynamic Motion Planning Modeler
Execute
Predict Dynamic Behavior
Store
Parameters Affect Dynamic Behavior
On-Line Interference Checking
Limits on Motion
Algorithms for Dynamic Behavior (Internal forces) (External Forces)
Incorporate
Check
Incorporate
Effect of: inertial forces, torques, bending, swaying, and vibration
Physical Properties
Incorporate
Modified Path-Finder
AI & 3D Computer Modeling Based System
Incorporate
Define Objects' Relations & Constraints
• relationships between objects
• constraints on manipulation mechanisms
• convention to set up local coor. frames
Assign
Equipment Degree of Freedom
Incorporate
Attach objects to manipulation mechanisms
Simulate
Generate
3D Computer Model
Objects
Equipments
3D Structural Modeler
Simulation & Control for Automation and Robotics
Single Operation Path Definition Files
Model Collision Free Path Stage
Multi-Tasking Conflict Resolution Stage
Simulate
Geometric & Graphics Data
Analyze
Animation of the Motion Operations
3D Computer Modeling
Execute
Identify Zones and Time Periods with Conflicts
Speed & Acceleration
Control of rigging Operation
Multiple Rigging in Const. Environments
Analyze
Optimize
Assess
Simulate
Analyze
Priority
Robot Control
Off-Line Programming Auto. Generation of Code
Program
Motion Plan
Generate
Generate Overall Plan
Incor-porate
Queuing Parameters
Type of Operation
Analyze
MTMP Output
Dynamic Motion Planning Modeler

Figure 2.1: Data Flow for the MTMP System (Beliveau et al. 1991)

thesis. The right half of the Figure 2.1 depicts the dynamic motion planner. The lower left quadrant represents the simulation and control for automation.

The theoretical aspects of the dynamic behavior modeler will be discussed in Chapter 4. A dynamic model of a material handling equipment (mobile crane) which is developed analytically will also be presented in Chapter 4. The other two major components of the MTMP system are presented in turn in this chapter. This chapter further looks at the significance of the MTMP system from both the technical and the application point of view.

2.1 The Dynamic Motion Planner

Creation of autonomous robots is one of the ultimate goals of robotics research. Progress towards this goal requires advances in many areas, including automatic reasoning, perception, and real-time control. Motion planning is one of the key topics in reasoning (Zhu and Latombe 1991).

Motion planning aims to provide objects (such as mechanical manipulators, robots, autonomous vehicles) with collision-free, cost-effective paths between a start and a goal position in clustered environments. Motion planning is quite a challenging task due to the objects' large number of degree of freedom. Throughout motion planning, another factor to be considered is the various costs and constraints associated with a path, such as length, safety, and time of completion. Therefore, management of these costs and constraints is an important issue for successful motion planning.

The "basic problem" - planning a collision-free path for a moving object among fixed obstacles - has attracted a lot of attention. Several approaches have been proposed, e.g., exact cell decomposition (Kedem and Sharir 1986), hierarchical approximate cell decomposition (Zhu and Latombe 1991), retraction (O'Dunlaing et al. 1983), potential field (Khatib 1986; Khosla and Volpe 1988). In the case of moving obstacles, Fujimura and Samet (Fujimura and Samet 1989) defined the extended space by adding time axis to 2-dimensional work space, and converted the moving obstacles of constant speed as static ones and then determined a collision-free trajectory in this extended space. Pan and Luo (Pan and Luo 1990) used the concept of traversability vectors to analyze the spatial relationship between the object and moving obstacles. In contrast with the collision avoidance schemes mentioned for a single mobile object, collision-free motion planning schemes for multiple objects are not many (Lee and Bien 1990; Chang et al. 1990). When the task needs two objects, collision may occur between the objects if the trajectories are planned independently, i.e. in the case of multiple robots some robots effectively become moving obstacles to others. Lee and Bien (Lee and Bien 1990) noted that, when the task needs more than two robots, the collision-free path of each robot may not be determined explicitly by the existing methods mentioned above. In particular, the coordination of designated paths are not easily accomplished. Extension of the existing methods for more than two robots is either simply impossible or extremely complicated to render any practical solutions. Heuristic methods such as allowing only one robot to move at one time or proposing safe robot trajectories to avoid the danger of collision between robots can be used for the collision avoidance of multiple robots. These schemes can be easily implemented, but usually do not take advantage of the capabilities of multiple robots satisfactorily (Chang et al. 1990).

It is evident that extensive research has been done in the area of motion planning. Traditional path planning systems generally have been concerned with single manipulation mechanisms in static environments. Attempts to extend these methods to environments containing multiple mobile objects are typically limited to gross movements in sparse environments or simplified shapes with few degrees of freedom to overcome the additional complexity. Particularly, the construction environments possess multiple (more than two) mobile material handling equipments with large degrees of freedom. And most of the time the material handling equipments are affected by external load conditions. However, the technologies developed so far do not seem sufficient to serve in a multi-tasking motion planning for material handling operations in construction. Thus, a motion planning modeler is needed which determines collision-free paths according to the dynamic characteristics of the construction environment. The dynamic motion planner proposed by Beliveau et al. (Beliveau et al. 1991) is envisioned to accomplish the task of motion planning for material handling equipment in construction.

The dynamic motion planner proposed by Beliveau et al. (Beliveau et al. 1991) aims to provide "multi-tasking motion planning for the movement of all material handling equipment within a construction environment during the process of executing different material handling tasks". To accomplish this goal, the dynamic motion planner will consider several constraints along with the effects of external load conditions during the process.

The dynamic behavior of the systems involved (i.e., material handling equipment and its associated material) will be analyzed during the motion process. This is accomplished by the dynamic behavior modeler which is presented in this thesis. The outcome of the analysis will have a critical impact on the selected path due to the deflection, swaying, etc. of the different components of the system. This analysis capability is of significance towards the goal of simulating a real-life performance. Moreover, the capability obtained by the integration of the dynamic behavior modeler and the dynamic motion planner is lacked by the technologies mentioned before in this section.

In the task environment, the material handling equipment motion encounters two types of constraints: geometry and time constraints (Pan and Luo 1990). Geometry constraints are imposed by static obstacles, while time constraints are imposed by moving obstacles. To resolve the geometry constraints, it is desired that the mechanism determines some routes that bypass static obstacles to reach its destination. When these routes are decided, occupancy of a path by moving obstacles can then be computed using 'traversability vectors'. The results can be registered in a distance-time space chart defined as the constraint map. Motion planning can be then treated as a 'pathfind' problem on this map. Another issue to be considered is the constraints on the degrees of freedom of the manipulation mechanisms which will affect the direction of the selected path. The degrees of freedom of the manipulation mechanisms will be considered before path finding process. This will overcome the problem of computing 'inverse kinematic' solutions for the manipulation mechanisms.

In addition, 'on-line' interference checking will be considered in the process of finding a collision-free path. The interference checking will be considered during all stages of the motion planning process, which is a complex process in a multi-task environment (Beliveau et al. 1991).

Beliveau et al. (Beliveau et al. 1991) indicate that "there are two approaches to plan for a collision-free path: mathematical and geometric/graphical". The mathematical approach is usually sophisticated and inefficient, especially in a multi-task construction environment. The geometric/graphical approach is simpler and efficient in such a environment, "especially if an on-line interference checking capability is incorporated".

The dynamic motion planner will employ a geometric/graphical approach to plan for the different paths and trajectories of the material handling equipment. This task will be accomplished in two stages. First stage is to model a collision-free path for each operation within the environment. All predefined constraints on the movement of the manipulation mechanisms will be considered during modeling. Second stage is to provide a conflict resolution capability between paths of different operations. Beliveau et al. (Beliveau et al. 1991) states that "the conflict resolution will utilize the concepts of process priorities, queuing parameters, kinematic attributes, etc."

2.1.1 Collision-Free Path Modeling

The dynamic motion planner will utilize in part the pathfinder that has been developed as part of WALKTHRU by Morad et al. (Morad et al. 1991). The current 'pathfinder' aims to find a feasible path for an object from one position and orientation in a 3-D computer model to another position and orientation. The path is optimized subject to motion constraints on mechanisms which manipulate the object and other objects. The pathfinder is based on an artificial intelligence approach that uses the state-space transformation representation with a 'generate-and-test' search strategy. The generate-and-test search is developed as a 'depth-first' strategy. The system defines an objective function which improves and expedites the search process by providing a directed-search approach (Beliveau et al. 1991). Appendix D provides a more detailed description of the current pathfinder strategy.

However, the current pathfinder needs to be modified to incorporate a more suitable search strategy to optimize the path finding process. This will significantly resolve issues related to implementing the generated path in a real-life situation by ensuring that the solution is a path along which the specified object can be moved using available equipment. The pathfinder will be able to efficiently provide a path solution which can be implemented on CAD systems. Beliveau et el. (Beliveau et al. 1991) point out the following issues which will be considered by the new search strategy:

- The dynamic behavior of the manipulation mechanisms and the transported objects. The analysis will be provided by the dynamic behavior modeler presented in this thesis.
- Degrees of freedom of the manipulation mechanisms.
- Movement limits of the manipulation mechanisms in the different directions of the degrees of freedom.
- An optimization function to select the most appropriate search fashion to fit the current situation within the environment (i.e., depth-first, breadth-first, or both, etc.).
- Incorporating a more accurate interference checking mechanism by using surface description rather than bounding boxes for volumes. This will be accomplished by incorporating integral properties of solids into WALKTHRU. This task is a major component for the development of the dynamic behavior, and discussed in Chapter 3.

According to Beliveau et al. (Beliveau et al. 1991), this stage will yield "a list of different paths that can be assigned to different manipulation mechanisms within the environment." Each path is generated assuming that there is only one process to be executed at a time. However, single process execution is not practical, because different operations are performed at the same time. Therefore, a capability is required to integrate the different paths in one plan to define a collision-free operation within the multi-task environment. This capability is the second stage of the dynamic motion planner: multi-tasking motion conflict resolution.

2.1.2 Multi-Tasking Motion Conflict Resolution

The second stage of the dynamic motion planner aims to evaluate and integrate the different paths generated by the pathfinder into a set of simultaneous operations such that no conflict in motion exists. The procedures required to identify the conflict areas will be developed. In addition, conflicts will be resolved to come up with a feasible solution that is free from conflicts (Beliveau et al. 1991).

To analyze conflicts and find a solution, the required procedures will utilize a simulation approach. The simulation is in the form of building mathematical, logical and graphical models. The following issues are identified by Beliveau et al. (Beliveau et al. 1991) as critical for conflict resolution.

- Identification of the zones and time periods within the work-space where multi-tasking motion conflicts exist.

- Establishment of priorities of different processes within the environment. Critical operations will be assigned higher priorities than less critical material handling processes.
- Analysis of different types of processes in terms of the continuity or the splitting of the process. Some processes can not be stopped once they have started because of safety, quality, or productivity constraints.
- Velocity and acceleration information in addition to position. This will give a new dimension to the path planning process, and provide the motion planning process with the ability to resolve a 4-D problem encompassing position and time. The velocity and acceleration of the manipulation mechanisms will affect safety and dynamic behavior of manipulation mechanisms. Limits and controls will be established in these areas.
- Development of a queuing model to plan the sequence of the operation to resolve the conflict between processes executed in the same congested area at the same time. Queuing parameters will be incorporated along with priority assignments.
- Development of a capability to provide alternative path strategies for certain sectors of the trajectory of a specific material handling process instead of queuing the process via stop-and-go alternative.

The multi-tasking motion conflict resolution stage will output a set of paths which are identified in terms of the trajectory and the location in space within a time domain. This stage will produce a feasible scenario to perform the various material handling processes in a congested environment. This scenario will enable the manipulation mechanisms and the materials transported by them to operate without colliding with each other and the surrounding environment (Beliveau et al. 1991).

When the manipulation mechanisms (such as robots) are required to do some task, 'control' is as essential as 'planning'. In the planning stage, the overall task of each manipulation mechanism is defined logically and quantitatively, and then the trajectory of each manipulation mechanism is planned in the work-space. In the control stage each manipulation mechanism should execute given tasks as planned. To achieve a better control of the operations, there are some processes, such as simulation and animation utilized in the control stage. The third major component of the MTMP system, simulation and control for automation/robotics utilizes a simulation system to model the environment and directly output control code for the multi-tasking automation process.

2.2 Simulation & Control for Automation /Robotics

As mentioned earlier in this chapter, the MTMP system will be a significant tool to achieve autonomous material handling operations. Simulation and control for automation/robotics component of the MTMP system will provide the required platform to automate the material handling operations in construction.

The development of simulation and control for automation/robotics will involve an 'off-line' robot programming facility capable of simulating material handling equipment behavior. Simulation and control for automation/robotics component will utilize the stored information about the kinematics and the physical properties of the objects within the environment. Beliveau et al. (Beliveau et al. 1991) state that "this will provide an effective tool for multi-tasking motion planning."

The material handling equipment and the workspace will be modeled in WALKTHRU, which was described in Section 1.5. 3-D computer modeling of the environment is an important issue, because the accuracy of modeling significantly affects the performance of the simulation and control for automation/robotics. Another important issue is the automatic code generation for material handling operations which is a significant step towards the automation of such operations. The following two sections will discuss these issues.

2.2.1 3-D Computer Modeling of Environment

The MTMP system will be built within WALKTHRU, and will support several commercial CAD/CAM software, such as CADAM, CATIA, AutoCAD, etc. Models from these systems can be directly transferred into WALKTHRU, and CAD drawings of objects can be loaded and manipulated in a single WALKTHRU layout. This makes it easy to model an environment in WALKTHRU.

The dynamic behavior modeler will provide input to compute the incremental frames at short time intervals within WALKTHRU. These incremental frames represent the changing environment. The interference checking will be done for each frame, and motion conflicts, if any, will be recorded. This will reduce the continuous non-linear time-varying problem of multiple mobile objects to a finite number of static frames. Each of these frames will be tested for interference. The interference checking will be hierarchical and will vary from a primitive proximity search using bounding boxes to a more complete interference detection at the surface level description. Because the tessellation and interference detection strategy are both variable, accuracy can be controlled interactively (Beliveau et al. 1991). This strategy has been used in earlier work on an AI based pathfinder which yielded good results for construction environments (Morad et al. 1991). The strategy was discussed before in Section 2.1.

The above mentioned facility will enable the user to perform a fast preliminary design, and efficiently plan material handling operations. This facility will provide the capability to perform a more accurate analysis as the design is refined. Once the analysis is performed, the stored frames are used to create a time based animation of activities. This animation can be seen as 3-D color shaded images showing objects in motion within the environment. Linear interpolation between these frames will display the animation in real-time. However, it should be noted that the interpolation performed is only to improve the speed, and does not affect the accuracy of the actual path. The actual path will be computed before the animation. Beliveau et al. (Beliveau et al. 1991) clarify that "although the prediction of the dynamic analysis is not performed in real-time, the animation helps in visualizing predicted behavior in real-time."

A complete, robust system, with suitable user interfaces will be developed to provide a tool for interactive multi-tasking motion planning. Libraries for standard material handling equipment and robots, along with tools such as grippers and hooks, etc. will be provided. These libraries will be open-ended to allow the user to add more objects. These libraries will enable modeling of material handling operations in a shorter time (Beliveau et al. 1991).

The following items are found to be critical to achieve a successful 3-D computer modeling of a material handling environment by Beliveau et al. (Beliveau et al. 1991).

- A library to store information on commonly used manipulation mechanisms. Suitable data structures will be developed to maintain such a library. The information stored will be the geometric data, ordered lists of links and joints, the associated physical properties, and the kinematic configuration of the manipulation mechanisms. The parent-child hierarchy of the links and the constraints on joint motions will also be stored. A facility will be provided to add the required objects to the library.
- A facility to retrieve any desired manipulation mechanism from the library to be used in the environment, and to be placed and manipulated as required.
- The dynamic behavior modeler to realistically visualize the material handling environment. The dynamic motion planner to generate collision-free paths between two positions. The dynamic motion planner will store the incremental motion along the available degrees of freedom for the recommended path. This will eliminate the need for computing the inverse kinematic solution. Hence, the system can have a wide range of applications for a variety of complex configurations.
- Capability to check interferences between objects within the environment at each stage, and report when necessary.
- A provision to attach other objects such as grippers, hooks, etc. to the manipulation mechanisms, i.e., robot end-effector.

2. The MTMP System Overview

- A provision to allow the user to backup and retrace the performed motion, if required. The object motion record capabilities of WALKTHRU will be used to store motion which can be replayed later.

Apart from 3-D computer modeling of material handling environment, automatic code generation is also a critical issue for simulation and control for automation/robotics. The following section will provide a look at that issue.

2.2.2 *Automatic Code Generation*

Automatic code generation is one of the major targets of the MTMP system to achieve autonomous material handling operations. It is believed that this automation will provide the capability to significantly improve the operations and safety of material handling equipment in construction. This section discusses the major issues involved in the development of automatic code generation for material handling operations.

Beliveau et al. (Beliveau et al. 1991) indicate that "there is no universally accepted neutral language for robot programming." Robot languages are generally specific to the manufacturer. Within the MTMP system, two-way interfaces with at least two commonly used languages will be developed. These interfaces will use the stored object motion file to generate code to control material handling equipment. The object motion file will be stored by the dynamic motion planner which was discussed in Section 2.1. The object motion file will contain the incremental steps along various degrees of freedom for the material handling equipment. Two-way interfaces will enable simulating objects' motions on the screen and help in automatically generating robot programs off-line from the stored object-motion file. This will enable to test the code before application (Beliveau et al. 1991).

Another major issue is to achieve reliable off-line programming. A provision will be made to incorporate workplace sensors, which will help overcome minor inaccuracies arising because of deflection, backlash, etc. This process is referred to as 'robot calibration'. Acceptable generic calibration procedures have not yet been resolved because of complexity involved in measuring relative positions and orientations. In the absence of calibration procedures, the system described above may not be able to achieve reliable autonomous programs for control of robots in a precision manufacturing shop-floor robot work cell. However, the system will have wide applications in material handling operations in construction for which available precision will be reliable (Beliveau et al. 1991).

Extensive research needs to be done to successfully complete simulation and control for automation/robotics component of the MTMP system. However, it should be noted that such a component undoubtedly is a valuable asset for multi-tasking motion planning in construction environments.

As stated before, the MTMP system will integrate a dynamic behavior modeler, a dynamic motion planner, and a simulation and control mechanism for automation/robotics. The aim of this integration is to better plan, model and control material handling operations. The dynamic motion planner and simulation and control mechanism for automation/robotics were discussed in the previous sections. The dynamic behavior modeler on which this thesis focuses will be discussed in Chapter 4. The following section looks at the significance of the MTMP system from both the technical and the application view points.

2.3 Expected Significance of the MTMP System

Once implemented, it is expected that the MTMP system will add a new dimension to the planning and execution of the material handling operations in construction. This new dimension possesses a smart and reliable approach to improve the performance (i.e., productivity, quality, timeliness and safety) of such operations. This automatically introduces significant improvements to constructability of the construction projects.

The MTMP system was proposed as a technically unique system. The elements that create this uniqueness are brought into the system mainly due to the nature of the construction environments. This uniqueness does not necessarily mean to invent new technologies, but instead may mean to modify or combine the existing technologies to achieve the objectives of the MTMP system.

The significance of the MTMP system can be reviewed from the view point of two areas. First, the technical significance of the system will be discussed. Then, the potential significant contributions of MTMP to the construction industry are presented.

2.3.1 Technical Significance

The primary aim of the MTMP system is to better plan, model, and control multi-tasking material handling operations in construction. To achieve this goal, several technologies, if necessary with modifications, will be integrated to develop MTMP. Currently, there is no available system which can accomplish a realistic multi-tasking motion planning for construction operations. It is expected that MTMP will not only accomplish this, but will generate automatic code to automate material handling operations. Hence, MTMP will be a technically unique system. The remainder of this section will review the technologies which are of significance in the development of the MTMP system.

The dynamic behavior component of MTMP will enable to model a realistic construction environment. So far, there has not been a motion planning system which takes into consideration the effects of both the external and the internal loads. The motion planning process of the MTMP system will consider the dynamic behavior of the mechanisms involved in the operations, equipment constraints on degrees of freedom and overloading, while checking for collisions. If paths are determined without considering these issues, they may not be applicable in practice due to the equipment constraints and deflections. This is particularly true for material handling in construction, since the material handling equipment manipulating the materials can be very large, and be affected by various loading conditions.

The MTMP system will provide a geometrically based solution to the motion planning problem instead of a mathematically based solution. Incremental frames describing the geometry of the changing environment are computed at short time intervals. Collision detection is performed for each individual frame to detect collisions. This reduces "the continuous non-linear time-varying problem of multiple objects in motion to a finite number of static problems" (Beliveau et al. 1991). Before continuing with the pathfinding strategy, an important point should be stated. When it is referred as 'multi-tasking' or 'multiple objects', it is meant that there may be more than two objects. However, as presented in Section 2.1.1 of this chapter, almost there has been no realistic motion planning for more than two objects. On the other hand, MTMP will provide motion planning for more than two objects, and this is a significant contribution to the multi-tasking motion planning process.

The MTMP system has "a novel approach to the pathfinding problem by eliminating the necessity to compute the inverse kinematic solution to move the equipment." Basically, the aim is to manipulate the equipment to move an object from initial position to the final position without collision and within specified constraints. This differs from the traditional approach of finding a collision-free path and then computing the inverse kinematic solutions to determine how the equipment is to be manipulated. In addition to this, the pathfinding strategy is based on moving the equipment incrementally along available degrees of freedom. Established parent-child hierarchies result in moving related parts of the equipment and the material. The path definition is in terms of the movement of the equipment joints, and hence, the sequence of joint actuation and incremental values of the joint movement are already known (Beliveau et al. 1991).

Another significant contribution provided by MTMP will be the direct code output to automate the overall material handling process. This task is performed by simulation and control component for automation/robotics. This component will enable MTMP to be interfaced with robot languages. Path information can be translated to automatically generate programs to control the material handling equipment. Besides, the MTMP system can be used to check the correctness of previous programs to avoid conflicts when two formerly distinct processes need to be combined at a later stage. The existing code can be fed to the MTMP system which performs a simulation and report conflicts, if any (Beliveau et al. 1991).

The implementation of the MTMP system will involve the use of the dynamic motion planner with interference detection, and conflict resolution capabilities. This is a part of developing a robust computer system for multi-tasking motion planning, complete with the dynamic behavior modeler. The final output of MTMP will be system generated code for manipulating material handling equipment.

This section reviewed the technical significance of the MTMP system. It should be noted that the technical characteristics of MTMP are heavily based on its application purposes. The significance of the system in applications is presented in the following section.

2.3.2 Significance in Applications

Construction projects generally involve many material handling operations. Transporting material with manipulation mechanisms without interferences and collisions is an essential task. To accomplish this task effectively, the integration of civil engineering knowledge with motion planning concepts and CAD/CAE tools is considered. This integration leads to an advanced and reliable tool, MTMP, which will be of significant help in multi-tasking motion planning for material handling operations in construction. Designers and constructors will better plan and control the overall material handling operations. The productivity, safety, quality, and timeliness of such operations will significantly improve. This further will lead to significant improvements in constructability.

Constructability is defined by The Constructability Task Force of the Construction Industry Institute (CII) as follows:

"the optimum use of construction knowledge and experience in planning, engineering, procurement and field operations to achieve overall objectives"

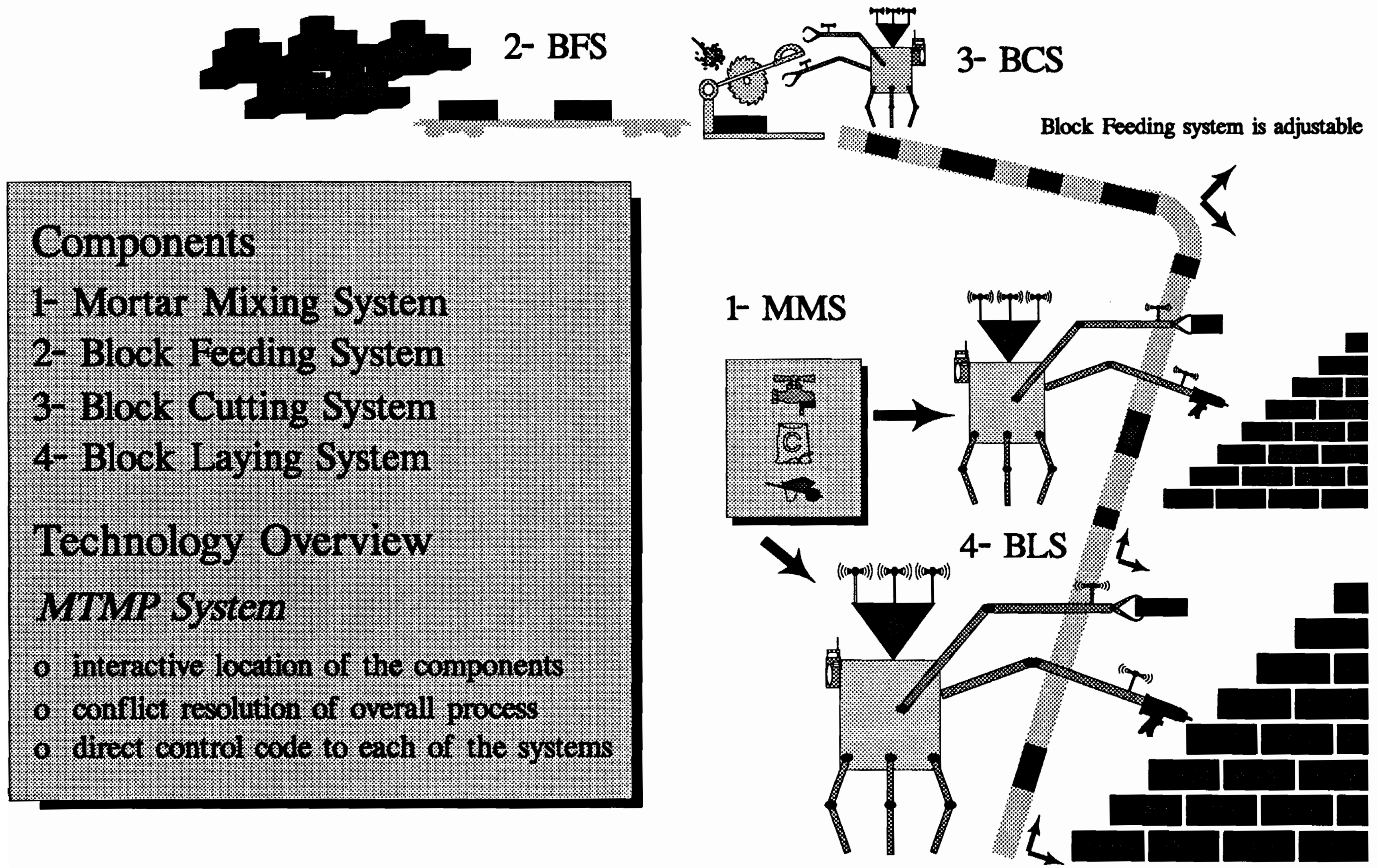
In order to avoid constructability problems (such as construction rework), it is necessary to evaluate constructability of each component at the planning stage, within the constraints of the equipment to be used. This is especially true for material handling operations. The MTMP system will be of significance in evaluation of the material handling operations at the planning stage of construction projects. For instance, the evaluations by means of MTMP will ensure that the scheduling process will generate a feasible sequence for such operations.

In addition to this, there are many ways that MTMP will help design professionals and constructors. The MTMP system will let them animate (simulate visually) the material handling operations during the design phase to avoid future constructability problems. With MTMP, they can test their initial sequencing of activities for constructability, and future sequencing due to out of sequence components. MTMP will help them efficiently organize complex construction operations where many material handling equipments (such as tower cranes, mobile cranes, forklifts) are involved. Provided with collision-free paths for these equipments, the designers will achieve significant improvements in the performance of such operations. Accidents and rework will be reduced, while safety and productivity will be improved, and timeliness will be ensured throughout the operations (Beliveau et al. 1991).

MTMP is a multi-path modeler for multi-tasking operations. The system determines the collision-free routes for the manipulation mechanisms involved in the material handling operations based on position and time. Therefore, if a conflict arises, e.g., two mobile cranes will interfere with each other, MTMP provides a strategy to avoid the conflict. This is done by assigning priorities to the equipment which performs the more critical activity. After the conflict is resolved, the MTMP system continues to determine feasible routes for the manipulation mechanisms.

The installation of a masonry structure is presented as an example of a construction application for MTMP. This example is taken from the proposal submitted to the National Science Foundation by Beliveau et al. (Beliveau et al. 1991). Although there are several strategies to build a masonry structure, only one of them is presented. A project consists of a mortar mixing system, a mortar delivery system, a block feeding system, a block cutting system, and two automated block laying machines. A starting location for the first block to be laid is required. All goal states are defined by the final location of each block. Figure 2.2 illustrates the installation of the masonry structure.

The MTMP system would be utilized to locate the components of the operation interactively. MTMP would provide a strategy to resolve potential conflicts of the overall process. Locations for each system as well as subsequent relocation during operations will be analyzed, and a feasible solution would be provided. Then, MTMP would provide direct control code to each of the systems to meet the goals of building the masonry structure. For fine adjustments of positions, and communication between systems sensor technology would be needed. This would enable the overall installation process to be fully automated.



Components

1- Mortar Mixing System
2- Block Feeding System
3- Block Cutting System
4- Block Laying System

Technology Overview

MTMP System

o interactive location of the components
o conflict resolution of overall process
o direct control code to each of the systems

Fig 2.2: Multiple Autonomous Vehicle Control for Masonry Construction

Beliveau et al. (Beliveau et al. 1991) also states that similar examples can be visualized in the area of multiple tower cranes for concrete placing operations, large steel fabrication cranes and machining operations, and control of multiple equipments in the hazardous waste clean-up industry.

Finally, the MTMP system will provide significant advances towards application for multi-rigging operations. Currently, there is no system which models how an object will roll or swing given the inertial forces. There is no system to model strains and stresses for each component of the material handling process in multi-rigging operations. MTMP will help in analysis and planning of multi-rigging operations where safety is an important issue. MTMP will help simulate a feasible solution while maintaining safe tolerances. The direct output of control information through MTMP will provide user augmented control. And with limited real-time sensing, planning of multi-rigging process will be significantly improved (Beliveau et al. 1991).

2.4 Summary

The MTMP system, proposed by Beliveau et al. (Beliveau et al. 1991) involves the technology required to provide a geometric solution to a multi-tasking motion planning system for material handling. This will be a reliable solution, and will significantly improve performance of the overall material handling operations. The improvements in the performance of such operations will undoubtedly improve the constructability of the construction projects. MTMP will also lay the basis for future research into multi-rigging issue with dynamic behavior analysis.

The significance of the MTMP system from both the technical and the application perspectives was discussed in the previous two sections. As mentioned in these sections, the application purpose of MTMP inspired and shaped the technical uniqueness of the system.

Multi-tasking motion planning in construction environments requires work in three areas: (1) modeling dynamic behavior, (2) motion planning, and (3) simulation and control for automation/robotics. The three components of the MTMP system are based on these areas. The dynamic motion planner and simulation and control system for automation/robotics were discussed in Sections 2.1 and 2.2 respectively.

Before looking at the theoretical aspects of the dynamic behavior modeler which is envisioned to be a major part of the MTMP system, this thesis will discuss the integral properties of solids issue in the next chapter. This issue is one of the several issues which are significant requirements for a realistic dynamic behavior modeler within WALKTHRU. The implementation of these issues will enhance WALKTHRU significantly, and enable WALKTHRU to be an efficient and effective platform for the MTMP system.

CHAPTER 3

INTEGRAL PROPERTIES OF SOLIDS ISSUE

The primary objective of this thesis has been identified as to provide a tool which helps visualize real-life performance of material handling operations in construction. This tool is a dynamic behavior modeler to perform dynamic simulation for computer animation. Such a tool is believed to model dynamic behavior of material handling equipments (such as mobile cranes) and potential robots found in construction. The theoretical aspects of the dynamic behavior modeler are presented further in the thesis.

There are several issues (integral properties of solids, object relationships and constraints, etc.) involved in the development of such a dynamic behavior modeler in WALKTHRU. Analysis and resolution of these issues will help in extending WALKTHRU from a visualization tool to an enhanced 3-D simulation and animation package with design and analysis capabilities.

One of these issues is the integral properties of solids. A realistic dynamic simulation within WALKTHRU heavily relies on incorporating integral properties of solids. An algorithm introduced by Lien and Kajiya (Lien and Kajiya 1984) is used as the strategy to incorporate integral properties of solids into WALKTHRU. This algorithm is programmed in C programming language. The program is tested, and the comparison of the results with the theoretical ones verifies the validity of the program. Due to its significance, and a considerable amount of effort put into this issue throughout this research, this issue will be discussed separately in this chapter.

In order to plan or control the static or dynamic behavior of models in CAD applications, it is necessary to evaluate integral properties (mass properties) of solid models (i.e. volume, centroid, moments of inertia, etc.). The evaluation of area, volume, centroid and moments of inertia of rigid homogeneous solids frequently arises in a large number of engineering applications, in CAD as well as in robotics.

Incorporating mass properties in a CAD system adds new levels for representing graphics objects. In addition to geometry -- forces, torques, velocities, accelerations, elastic behaviors, kinetic and potential energies and other physical properties are used to control the creation and evolution of solid models.

The integral properties of the solids issue together with the object relationships and constraints issue is an essential component for the development of the dynamic behavior modeler. As a consequence, the development of the MTMP system depends heavily on incorporating integral properties to WALKTHRU.

The first section of this chapter gives background and reviews the work that has been done in the evaluation of integral properties of solids. The evaluation of such properties depends on the representation schemes involved in the CAD systems. The boundary representation scheme which is used in WALKTHRU is discussed in Section 3.2. Following this section, the strategy employed to convert hollow surface models of WALKTHRU to solid objects having mass properties is discussed in Section 3.3. The implementation of the strategy is presented in Section 3.4. Finally, Section 3.5 provides a summary about the integral properties issue.

3.1 Background and Literature Review

The volume, area, center of mass, moments of inertia, and similar properties of solids are defined by triple (volumetric) integrals over subsets of three-dimensional Euclidean space. This section reviews methods for evaluating triple integrals of the form

$$I = \int_s f(P)\, dV \qquad (3\text{-}1)$$

where P = (x,y,z) is a point of Euclidean 3-space (E^3), dV is the volume differential, f is a simple real-valued scalar function, e.g., a polynomial, and *S* is a solid that may be geometrically complex, (e.g., a typical mechanical part bounded by many curved faces).

Integrals of this nature arise in many areas of engineering and physics. In CAD, for example, the mass properties of a homogeneous mechanical part *S* of density μ and mass *m* are defined by Equation (3-1) when

$f(P) = \mu$: $I = m$, or volume when $\mu = 1$ (3-2a)

$f(P) = x / m$: $I = x$-coordinate of barycenter (3-2b)

$f(P) = x^2 + y^2$: I = moment of inertia about z (3-2c)

..etc.

Quadrature formulas for multiple integration have always been of great interest in computer applications (Stroud 1967, Krylov 1962). Various attempts have been made in order to get practical formulas over simplicial complexes. Numerical integration over simplices has been discussed by Hammer and Stroud (Hammer and Stroud 1956), who obtained exact formulas for the quadratic and cubic polynomials over n-simplices in the n-space. But the extension of them for the integration of higher degree polynomials offers, according to the authors, "significantly greater complexity".

Several papers on integration relate to solid modeling. As Lee and Requicha (Lee and Requicha 1982) pointed out most computational studies of multiple integrals deal with problems in which the domain *S* (Equation 3-1) is geometrically simple, e.g., a cube or sphere, but the integrand f is complicated. However, in the calculation of mass properties the function f is usually simple but the domain *S* may be very complicated (Braid 1973).

Lee and Requicha (Lee and Requicha 1982) also stated that in evaluating mass property integrals over complicated solids

1) The particular means used to represent solids dominate the design of algorithms.

2) Errors attributable to approximations in representing solids usually dominate errors from more traditional and well-studied sources, e.g., round-off, truncation, numerical cancellation, and approximate integration formulas.

In their paper, Lee and Requicha (Lee and Requicha 1982) have reviewed several representation-oriented algorithms for evaluating the triple integral described above. The known methods for representing solids include primitive instancing, disjoint decomposition, constructive solid geometry, simple sweeping, and boundary representation. Each of these methods posses particular difficulties in the transfer of theory into practical application.

Objects described by primitive instancing belong to a finite number of primitive solid families, each of which is characterized by a finite number of parameters. Algorithms for computing integral properties of objects represented by primitive instancing are primitive specific: that is a special formula or method is developed for each primitive. As the number and complexity of primitives in a representation scheme increases, the programming effort and the size of the software library also increases.

Decomposition methods suffer from similar drawbacks. Disjoint decomposition partitions a solid into smaller solids. Three-dimensional triangulation decomposes a solid into a union of tetrahedra. Octree decompositions (Jackins and Tanimoto 1980) generate displays of cubical solids whose linear dimensions are power-of-two multiples of some minimal size. An integral over a solid is then the sum of integrals over each small solid. However, generating an appropriate decomposition for a solid is usually expensive and requires considerable human labor and computation time.

3. Integral Properties of Solids Issue

Likewise, constructive solid geometry (CSG) representation suffers from some relative inefficiencies. In this scheme, objects are described by the union, intersection, and difference of primitive solids. A CSG representation is a tree with "branching nodes" which represent operators and "leaves" which represent primitive solids. Lee and Requicha (Lee and Requicha 1982) have exploited a divide-and-conquer method for computing the integral properties of solids represented by CSG. Nevertheless, their method involves extensive computational time.

Other methods, though theoretically exact, may stretch programming skills to their limit. Sweeping representations describe a volume by an object moving along a trajectory, generally with translational and/or rotational motions. The integral properties of solids represented by translational and rotational sweeping may be computed by exploiting dimensional separability to convert a triple integral into a double integral. However, Lien and Kajiya (Lien and Kajiya 1984) have stated that it remains a difficult challenge to devise a convenient algorithm for this technique.

Finally, some methods trade exactness for efficiency. Integral properties of solids represented by boundary representation can be evaluated by generating a collection of quasi-disjoint cells whose union approximates the solid, and computing the integral properties of the solid by adding the contributions of each individual cell. Wilson and Farrior (Wilson and Farrior 1976) presented formulas for the computation of main geometrical and inertial properties of planar polygons and of rotational solids. O'Leary (O'Leary 1982) developed quadrature formulas based on a quasi-disjoint decomposition of the solid in volume elements of simple predefined shape. Timmer and Stern (Timmer and Stern 1980) discussed a theoretical approach to the evaluation of domain integrals over a boundary representation of solids. Cohen and Hickey (Cohen and Hickey 1982) introduced two algorithms for computing volumes of convex polyhedra. The first algorithm consists of triangulating a given solid into simplices and adding their individual volumes together. This algorithm, however, is not applicable to the calculation of arbitrary polynomial functions. The second algorithm is of the Monte Carlo genre but is specialized to take advantage of the convexity of polyhedra. However, the result is approximate, and accuracy can be increased only at the expense of additional computer time. Lien and Kajiya (Lien and Kajiya 1984) showed a closed formula for volume integration by decomposing the solid into a set of solid tetrahedra, but they did not handle the problem of surface integration. Paoluzzi et al. (Paoluzzi et al. 1989) presented a method which might be considered as a specialization of Timmer and Stern's general method, consisting of the transformation of a volume integral into a surface integral and then into a parametric line integral. The authors gave a symbolic solution both to the surface and to the volume integration of polynomials by triangulation of the volume boundary.

The review and study of the research that has been done in the evaluation of integral properties of solids has clarified the strategy to incorporate these properties into WALKTHRU. Due to its simple and systematic characteristic, and easy implementation, the method introduced by Lien and Kajiya (Lien and Kajiya 1984) was selected as the strategy. This method also stands as the most appropriate strategy, considering the representation of objects in WALKTHRU.

In this research, a significant task has been to incorporate these properties into WALKTHRU which is the environment for the development of MTMP. The objects in WALKTHRU are represented by boundary representation scheme. Thus, the strategy to be employed must take the characteristics of boundary representation scheme into account. Lien and Kajiya's method fulfills this requirement. Before presenting the strategy used to incorporate integral properties of solids into WALKTHRU, the following section gives brief information about boundary representation, and discusses the possible methods to evaluate integral properties in the case of boundary representation.

3.2 Boundary Representation Scheme

As stated earlier, the algorithm(s) required to incorporate the integral properties of solids into a CAD system is designed according to the particular means used to represent solids within the system.

Representation schemes for three-dimensional objects can be classified into two major categories: volumetric and boundary representations (Requicha 1980). Volumetric representation techniques describe an object as a combination of primitive volumes. This class includes all the decomposition techniques related to the underlying space representation, such as occupancy arrays and octree encoding (Meagher 1982), and object-based techniques related to predefined primitive volume elements. These techniques are not directly tied to the coordinate system, such as constructive solid geometry techniques (Requicha 1980). Boundary (or surface-based) representation (B-Rep) techniques describe solid volumes in terms of their enclosing surfaces. Such models can be called solid models when they completely describe the form and the extent of the individual oriented surface of the objects. They must also contain enough information to determine how the surfaces are joined together to form completely closed and connected volumes.

A boundary representation of an object is a geometric and topological description of its boundary, which is segmented into a finite number of bounded subsets, called "faces" as shown in Figure 3.1. Each face is, in turn, represented by its bounding "edges" and "vertices". Thus, a boundary model is composed of three primitive elements: faces, edges, and vertices. Faces are contiguous surface areas of the volume enclosed by boundaries. Edges are the elements that, when joined together, form the closed face boundaries. Vertices are those points on the surface at which edges intersect. B-Rep scheme maintains detailed topological data with respect to the face-edge-vertex relation as an internal description of an object. Thus, the model can adapt itself easily to any stage of design and manufacturing; also it can treat a three-dimensional object of any shape.

Boundary models are the most widely used representations of solid objects in many application domains. They have some important properties that make their use within a geometric model very attractive. Boundary schemes have wide applicability; they are complete and also unique, provided that a partition of the boundary into maximal faces is considered (De Floriani and Falcidieno 1988). Furthermore, they are sensitive, in the sense that they are able to represent finer characteristics of an object.

Apart from geometric consideration, this section further discusses below the methods to evaluate integral properties of solids represented by boundary representation scheme. Integral properties of solids represented by their boundaries may be evaluated by surface integration, using either direct integration or the divergence theorem of vector calculus. (These two methods are closely related).

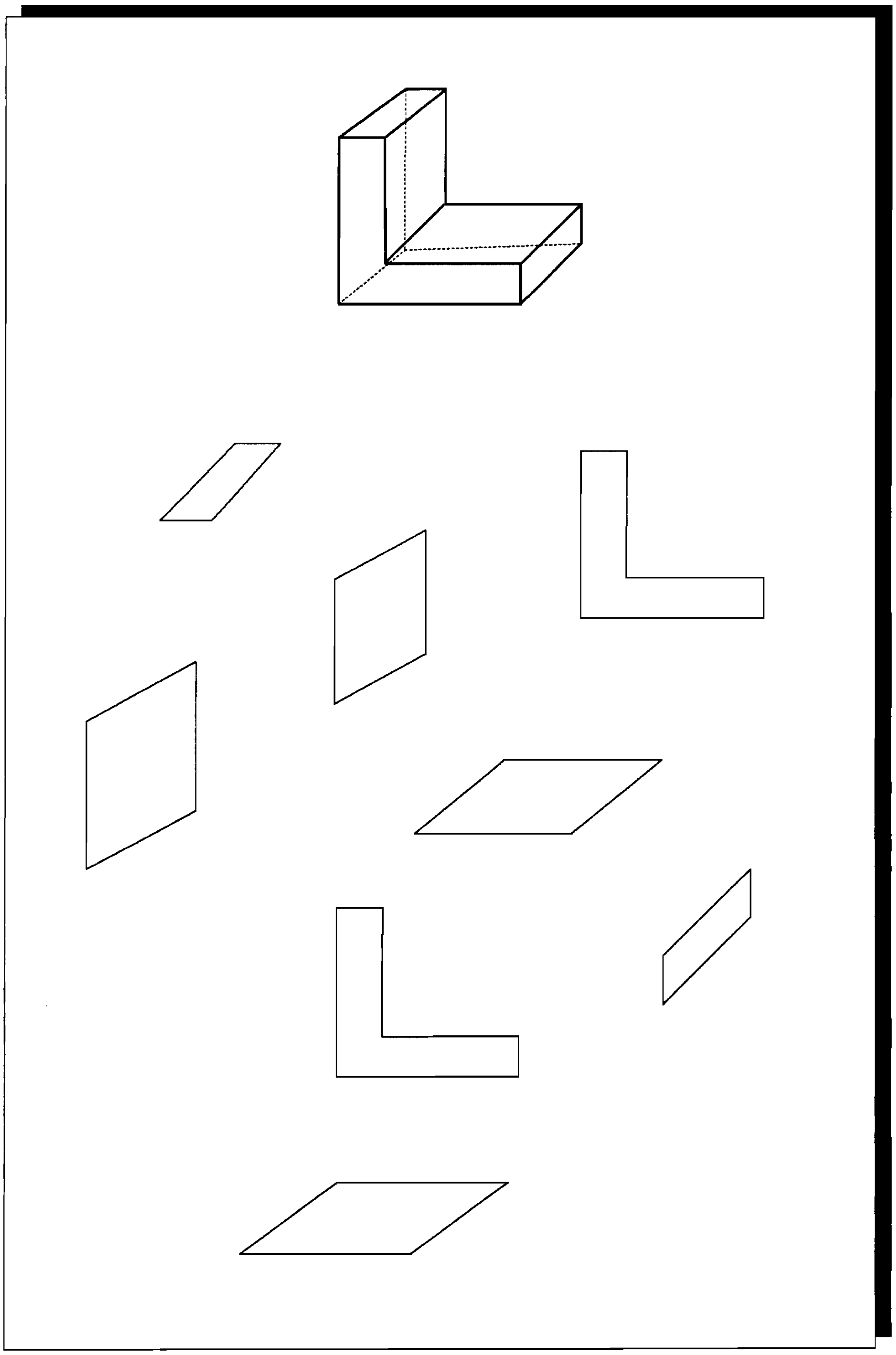


Figure 3.1: The Boundary Representation of a Solid

Direct integration is the standard technique discussed in calculus textbooks. For example, the integral of a function *f(x,y,z)* over the polyhedral solid depicted in Figure 3.2 may be evaluated by adding the appropriately signed contributions of the prisms defined by the faces and their *xy* projections. The contribution of face F_i in Figure 3.2 is the integral

$$-\int_{F_i'}\int dxdy \int_0^{z_i(x,y)} f(x,y,z)\, dz \qquad (3\text{-}3)$$

where F_i' is the *xy* projection of face F_i and $z_i(x,y)$ is obtained by solving for z in the equation of the plane in which F_i lies. (Instead of a parallel projection of the object, one can use a central projection and add the contributions of the pyramids defined by the center of projection and object's faces (Wesley 1980); choosing a center of projection inside the object is likely to minimize round-off errors). A similar technique can be used to evaluate the contribution of each edge of F_i' to the integral Equation (3-3).

The method just described is attractive for polyhedral solids, but for curved solids several difficulties arise:

- Faces may have to be segmented to ensure that z_i is a (single-valued) function of (x,y).
- It may be difficult or impossible to solve the surface equations for z and/or to evaluate (symbolically) the rightmost, one-dimensional integrals in Equation (3-3).
- The equations of the curves that bound the projected faces F'_i may not be available.

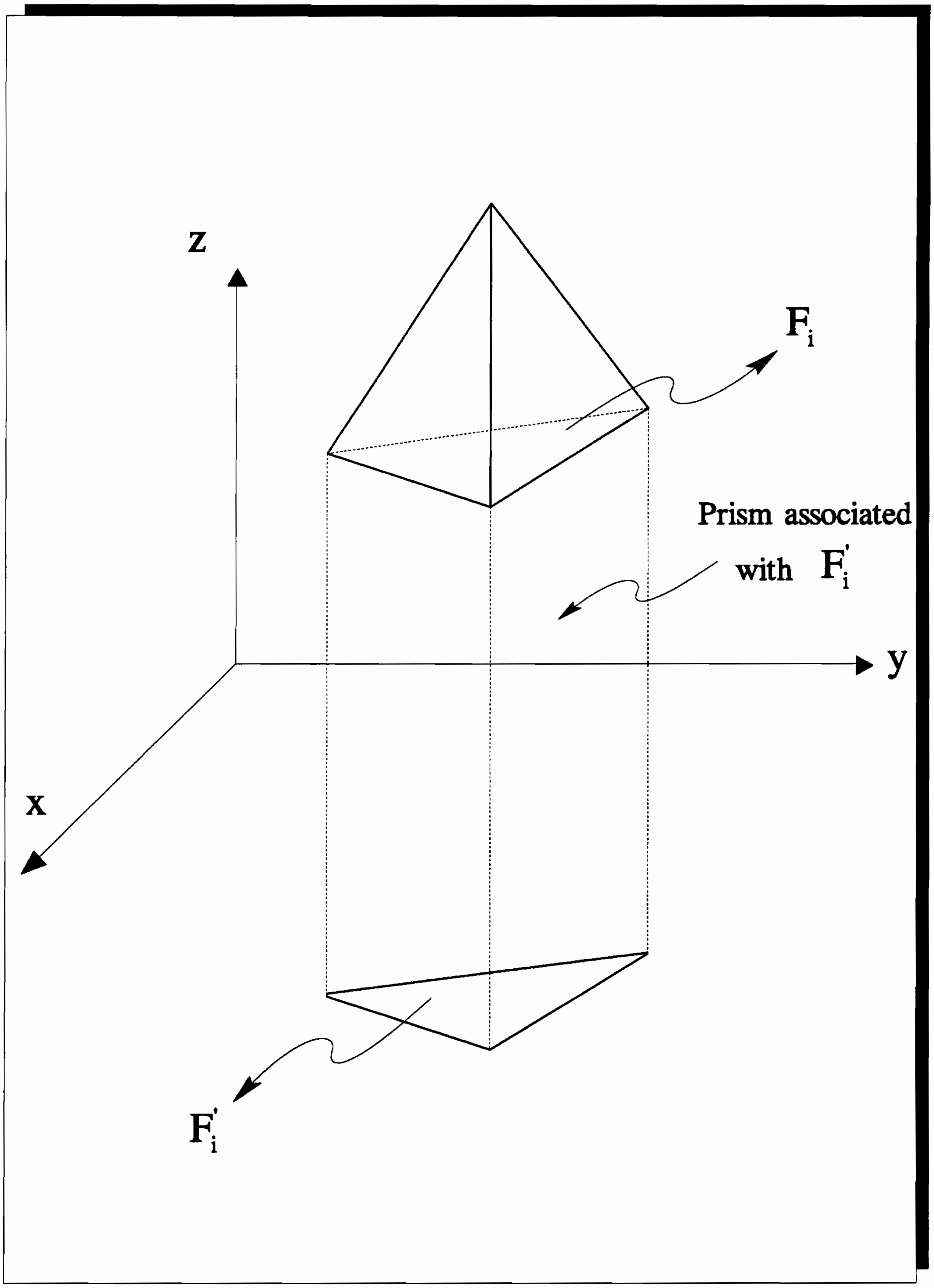


Figure 3.2: Method of Direct Integration

The last difficulty may be resolved by approximating the bounding curves with straight line segments (Braid 1973), but estimates of the errors that are introduced in integral property calculations by such approximations are not available (Lee and Requicha 1982).

The divergence theorem provides an alternative method for evaluating the integral properties of solids represented by their boundaries. For any given continuous function *f(x,y,z)* it is always possible to find a vector function *g(x,y,z)* such that div $g = f$. It follows from the divergence theorem that

$$\int_S f\,dV = \int_S \operatorname{div} g\,dV = \sum_i \int_{F_i} g.n_i\,dF_i \qquad (3\text{-}4)$$

where F_i is a face of the solid S, n_i is the unit vector normal to F_i, and dF_i is the surface differential. When the faces F_i are planar polygons, the integrals on the right side of Equation (3-4) are not complex to evaluate.

Curved objects can be accommodated by approximating the objects' faces with triangular facets (Messner 1970, Messner and Taylor 1980), but the errors introduced by such approximations have not been analyzed. An alternative procedure is available (Timmer and Stern 1980) for dealing with objects whose faces are subjects of parametrically defined patches bounded by parametrically defined edges.

Specifically, the contribution of each face is evaluated by changing variables in the surface integrals in the right side of Equation (3-4), the results are converted into path integrals via Green's theorem, and the path integrals are evaluated by approximate integration formulas.

In summary, both direct integration and divergence theorem methods are attractive and have been used for *polyhedral objects* represented by their boundaries. Curved objects can be accommodated either through polyhedral approximation or approximate integration over surface patches; the errors introduced by such techniques do not appear to have been analyzed.

The strategy employed in this research uses the direct integration technique to evaluate the integral properties of solids. The direct integration technique reduces the complexity of the evaluation process. Provided that it is coupled with an appropriate triangulation algorithm, the strategy involving direct integration technique is certainly efficient to incorporate integral properties of solids into WALKTHRU, and yields satisfactory results. The strategy used to compute integral properties of solids is discussed in the following section.

3.3 Calculation of Integral Properties

This section presents the strategy employed to incorporate integral properties of solids into WALKTHRU. The strategy depends on the method introduced by Lien and Kajiya (Lien and Kajiya 1984). This is a simple and systematic method for evaluating the integral of an arbitrary polynomial function over an arbitrary polyhedron represented by boundary representation. The implementation of the method is also very simple. Particular characteristics of the method (such as direct integration technique) has led to the selection of this method as the strategy. The characteristics of the method, along with its derivation are presented in this section. Section 3.1.4 will discuss the implementation of the strategy.

A general formula for direct evaluation of the integral of a polynomial over a 3-D simplex is presented first. An integral over a polyhedron can then be easily calculated by using the central projection method and decomposing a polyhedron systematically into a set of simplices and accumulating the results from each simplex based on this formula. This method adopts a systematic and automatic decomposition. It is analytically exact but the practical accuracy of the result is within the accuracy of floating-point arithmetic. Furthermore, the time complexity of this method is linearly proportional to the number of vertices of a polyhedron.

Symbolic Evaluation

The area of triangle T with vertices (v_0, v_1, v_2) is equal to the cross product of the vectors $\mathbf{r}_1 = (v_0, v_1)$ and $\mathbf{r}_2 = (v_0, v_2)$:

$$\text{Area (T)} = 1/2\ (\mathbf{r}_1 \times \mathbf{r}_2) = 1/2\ (y_1 z_2 - y_2 z_1,\ z_1 x_2 - x_1 z_2,\ x_1 y_2 - x_2 y_1) \qquad (3\text{-}5)$$

where $\mathbf{r}_1 = (x_1, y_1, z_1)$ and $\mathbf{r}_2 = (x_2, y_2, z_2)$.

Here the symbol x denotes the cross product of two vectors. The area is defined as a vector that not only has a quantity but also an associated orientation. The area of an arbitrary closed planar region R is

$$\text{Area (R)} = 1/2 \int_{\partial R} r \times dl \qquad (3\text{-}6)$$

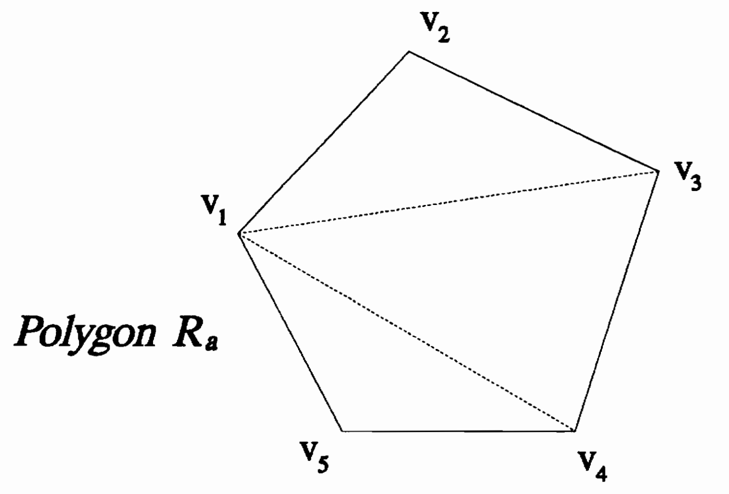
where ∂R is the boundary of the region R and **dl** is the differential tangent vector of the boundary. The area of the planar polygon $R = (v_1, v_2, .., v_n)$ with n vertices $\{v_i = (x_i, y_i, z_i)\}$, is

$$\text{Area}(R) = 1/2 \int_{\partial R} r \times dl$$

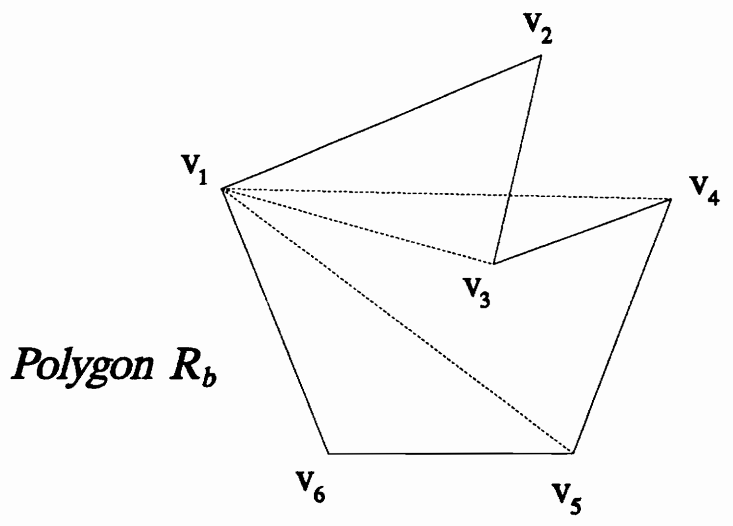
$$= 1/2 \sum_{i=1}^{n-2} (v_1, v_{i+1}) \times (v_1, v_{i+2}) \quad (3\text{-}7)$$

Using v_1 as a projection origin, the planar polygon is dissected sequentially into a series of triangles formed by v_1 and each directed edge of the polygon in sequence. The area of the polygon is the vector sum of the areas of all triangles as defined in Equation (3-5). The dissected triangles are not necessarily mutually disjoint, however, if a polygon is concave. Equation (3-7) nevertheless holds for either convex or nonconvex polygons.

For example, in Figure 3.3(a), polygon R_a is a convex polygon composed of five vertices. Using v_1 as a projection origin, R_a is dissected sequentially into three triangles $\{T_i = (v_1, v_{i+1}, v_{i+2})\}$ for i = 1, 2, 3. The area of R_a is equal to the sum of the areas of all triangles. In Figure 3.3(b), polygon R_b is concave and composed of six vertices. R_b can be dissected into four triangles $\{T_i = (v_1, v_{i+1}, v_{i+2})\}$ for i = 1, .., 4, where the triangles $T_1 = (v_1, v_2, v_3)$ and $T_2 = (v_1, v_3, v_4)$ are not disjoint. The area of R_b is equal to the sum of the appropriately signed areas of all triangles, i.e., $R_b = T_1 - T_2 + T_3 + T_4$.



(a) a convex polygon composed of five vertices and dissected into three triangles



(b) a concave polygon composed of six vertices and dissected into four triangles

Figure 3.3: Convex and Concave Polygons

The integral properties of a polyhedron Q can be described by

$$I = \int_Q f(x,y,z)\, dv \qquad (3\text{-}8)$$

where function f is a polynomial. With a linear transformation defined as

$$x = g_x\,(u, v, w)$$

$$y = g_y\,(u, v, w)$$

$$z = g_z\,(u, v, w)$$

Equation (3-8) becomes

$$I = \int\int\int_Q f(g_x, g_y, g_z)\, | J |\, dudvdw \qquad (3\text{-}9)$$

where the Jacobian J

$$J = \begin{vmatrix} \frac{\partial g_x}{\partial u} & \frac{\partial g_x}{\partial v} & \frac{\partial g_x}{\partial w} \\ \frac{\partial g_y}{\partial u} & \frac{\partial g_y}{\partial v} & \frac{\partial g_y}{\partial w} \\ \frac{\partial g_z}{\partial u} & \frac{\partial g_z}{\partial v} & \frac{\partial g_z}{\partial w} \end{vmatrix} \qquad (3\text{-}10)$$

The integrand f in Equation (3-8) is a polynomial that can be generally represented as

$$f(x,y,z) = \sum_{n_1,n_2,n_3} x^{n_1}y^{n_2}z^{n_3},$$

where n_1, n_2, and n_3 are integers.

To compute the integral in Equation (3-8), only one typical term is taken:

$$I = \int\int\int_Q x^{n_1}y^{n_2}z^{n_3}\, dxdydz \qquad (3\text{-}11)$$

As a simple case, Q can be considered as a 3-D simplex (i.e., a tetrahedron) with four vertices (v_0, v_1, v_2, v_3), and the vertex v_0 is located at the origin. The coordinates of the vertices are

$$v_0 = (0,0,0)$$

$$v_1 = (x_1, y_1, z_1)$$

$$v_2 = (x_2, y_2, z_2)$$

$$v_3 = (x_3, y_3, z_3)$$

A linear transformation **T** can be defined as

$$\mathbf{T} = \begin{pmatrix} x_1 & x_2 & x_3 \\ y_1 & y_2 & y_3 \\ z_1 & z_2 & z_3 \end{pmatrix} \qquad (3\text{-}12)$$

which relates the old coordinate system (x, y, z) with the new system (X, Y, Z) by

$$\begin{pmatrix} x \\ y \\ z \end{pmatrix} = \begin{pmatrix} x_1 & x_2 & x_3 \\ y_1 & y_2 & y_3 \\ z_1 & z_2 & z_3 \end{pmatrix} \begin{pmatrix} X \\ Y \\ Z \end{pmatrix} \qquad (3\text{-}13)$$

The original tetrahedron Q is now transformed by **T** into an orthogonal unit tetrahedron, $W = (v_0', v_1', v_2', v_3')$ with coordinates

$$v_0' = (0,0,0)$$

$$v_1' = (x_1, y_1, z_1)$$

$$v_2' = (x_2, y_2, z_2)$$

$$v_3' = (x_3, y_3, z_3)$$

Based on the transformation in Equation (3-9), the integral in Equation (3-11) becomes

$$I = \| T \| \int\int\int_W (x_1X+x_2Y+x_3Z)^{n_1} (y_1X+y_2Y+y_3Z)^{n_2} (z_1X+z_2Y+z_3Z)^{n_3} \, dXdYdZ \quad (3\text{-}14)$$

where the Jacobian $\| T \|$ is equal to the absolute value of the determinant of the matrix **T**.

Next, a formula for evaluating the integral of a polynomial x^{n1} y^{n2} z^{n3} over an orthogonal unit tetrahedron W is presented.

$$\int_W x^{n_1}y^{n_2}z^{n_3}\, dv$$

$$= \int_0^1 \int_0^{1-z} \int_0^{1-z-y} x^{n_1}y^{n_2}z^{n_3}\, dx\, dy\, dz \qquad (3\text{-}15)$$

$$= \frac{n_1!\, n_2!\, n_3!}{(n_1+n_2+n_3+3)!}$$

An arbitrary tetrahedron can always be transformed to an orthogonal unit tetrahedron by means of a simplex-dependent transformation matrix **T** as in Equation (3-12). Therefore, an integral of a polynomial over a tetrahedron can be evaluated by Equations (3-14) and (3-15).

To calculate the integral in Equation (3-14), first of all the integrand is decomposed to the following

$$I = \| T \| \sum_i \sum_j \sum_k c(i,j,k) \int_W X^i Y^j Z^k\, dV \qquad (3\text{-}16)$$

$$= \| T \| \sum_i \sum_j \sum_k c(i,j,k) \frac{i!\, j!\, k!}{(i+j+k+3)!}$$

Here the function c(i, j, k) represents the coefficient of a term $X^i Y^j Z^k$ in the expansion of the integrand, which can be loosely described by

$$(x_1x+x_2y+x_3z)^{n_1}(y_1x+y_2y+y_3z)^{n_2}(z_1x+z_2y+z_3z)^{n_3}$$

$$= \sum_{i+j+k=n_1+n_2+n_3} c(i+j+k)x^iy^jz^k$$

The volume, center of mass, and moments of inertia of a 3-D simplex can be therefore evaluated as follows:

The volume of a tetrahedron Q is

$$V = \int_Q dv = \| T \| \int_W dV = \| T \| \frac{0!}{3!} = \frac{\| T \|}{6} \qquad (3\text{-}17)$$

The barycenter ($\mathbf{x_o}$, $\mathbf{y_o}$, $\mathbf{z_o}$) of the tetrahedron Q is

$$\mathbf{x_o} = 1/4\ (x_1+x_2+x_3) \qquad (3\text{-}18)$$

$$\mathbf{y_o} = 1/4\ (y_1+y_2+y_3) \qquad (3\text{-}19)$$

$$\mathbf{z_o} = 1/4\ (z_1+z_2+z_3) \qquad (3\text{-}20)$$

The mass moments of inertia of the tetrahedron Q are

$$I_{xx} = \int_Q y^2 dv + \int_Q z^2 dv \qquad (3\text{-}21)$$

$$I_{yy} = \int_Q x^2 dv + \int_Q z^2 dv \qquad (3\text{-}22)$$

$$I_{zz} = \int_Q x^2 dv + \int_Q y^2 dv \qquad (3\text{-}23)$$

where

$$\int_Q x^2\, dv = \frac{V}{10}\,(x_1^2+x_2^2+x_3^2+x_1x_2+x_1x_3+x_2x_3)$$

$$\int_Q y^2\, dv = \frac{V}{10}\,(y_1^2+y_2^2+y_3^2+y_1y_2+y_1y_3+y_2y_3)$$

$$\int_Q z^2\, dv = \frac{V}{10}\,(z_1^2+z_2^2+z_3^2+z_1z_2+z_1z_3+z_2z_3)$$

The product moments of inertia of the tetrahedron Q are

$$I_{xy}= \int_Q xy\, dv = \frac{V}{20}[2(x_1y_1+x_2y_2+x_3y_3) + (x_1y_2+x_2y_1+x_1y_3+x_3y_1+x_2y_3+x_3y_2)] \qquad (3\text{-}24)$$

$$I_{xz}= \int_Q xz\, dv = \frac{V}{20}[2(x_1z_1+x_2z_2+x_3z_3) + (x_1z_2+x_2z_1+x_1z_3+x_3z_1+x_2z_3+x_3z_2)] \qquad (3\text{-}25)$$

$$I_{zy} = \int_Q zy\,dv = \frac{V}{20}[2(z_1y_1+z_2y_2+z_3y_3)$$
$$+ (z_1y_2+z_2y_1+z_1y_3+z_3y_1+z_2y_3+z_3y_2)] \qquad (3\text{-}26)$$

3.4 Implementation of the Strategy

The method developed by Lien and Kajiya (Lien and Kajiya 1984) for calculating the integral of a polynomial function over an arbitrary nonconvex polyhedron is simple and systematic. Computation is divided into integrals over a set of cones formed by the faces of the polyhedron with respect to the origin. An integral over the cone is then divided into integrals over a set of tetrahedra formed by the triangles dissected from the face with respect to the origin.

Although Equations (3-14) and (3-15) look complicated, the basic idea is very simple. Equation (3-15) supplies a direct solution to the evaluation of the integral of a polynomial function f(x, y, z) = $x^{n1}\ y^{n2}\ z^{n3}$ over an orthogonal unit tetrahedron. Equation (3-14) then shows that an arbitrary tetrahedron can be transformed to an orthogonal unit tetrahedron; therefore, an integral over the tetrahedron can be computed on the basis of the result from Equation (3-15).

The implementation of the method is also very simple. The computation involves sequential scanning over the faces of polyhedron and sequential dissecting of the faces into triangles. Since a face F_i with e_i edges is dissected sequentially into (e_i - 2) triangles, it requires $\Sigma(e_i - 2)$ computations. Since an edge is counted twice during the whole scanning procedure, the following relation is obtained:

$$\sum_{F_i} (e_i - 2) = 2E - 2F$$

where E is the total number of edges and F is the total number of faces of the polyhedron. According to the Euler equation, in which $V - E + F = 2$, the total number of computations is equal to $2(V - 2)$, i.e.,

$$\sum_{F_i} (e_i - 2) = 2(V - 2)$$

Therefore, the time complexity of the method is linearly proportional to V, the number of vertices of the polyhedron. Another important aspect about vertices is their order. The order of vertices in each face should be specified clockwise so that the normal vector always points away from the tetrahedron. This is necessary, because the current version of WALKTHRU does not have the capability to determine the direction of the normal vectors, thus leading to possible miscalculations of integral properties of solids. However, a "ray tracing" algorithm can be implemented into WALKTHRU to take care of this problem. By means of such a facility, it is possible to determine the direction of the surface normals.

The algorithm introduced by Lien and Kajiya (Lien and Kajiya 1984) is coded in C programming language. This C program is presented in Appendix B.

Due to the nature of the strategy, there is a need for a triangulation algorithm to dissect the faces of the polygons into triangles. An algorithm developed at Virginia Tech is utilized for this purpose. This algorithm has been developed for a project funded by Bechtel, Inc. Appendix A describes the triangulation algorithm briefly.

As for the final remarks, the numerical accuracy of the method can be improved by shifting the origin of the coordinate system to the barycenter of the object, especially to prevent the occurrence of long, thin tetrahedra when an object is far removed from the origin. Also, the method can be generalized to solids in higher dimensions. Its computation time does not increase linearly with the number of integral quantities computed, since only one matrix determinant $| \mathbf{T} |$ needs to be computed when several integral quantities are calculated at the same time.

3.5 Summary

Evaluation of integral properties of solids is required to plan or control the static or dynamic behavior of models in CAD applications. Such a capability is undoubtedly an essential part of the dynamic behavior modeler envisioned in the MTMP system.

A method introduced by Lien and Kajiya (Lien and Kajiya 1984) is used as the strategy to incorporate the integral properties of solids into WALKTHRU, the platform for MTMP. The algorithm is coded in C programming language, and the program yields satisfactory results.

As mentioned earlier, in addition to integral properties of solids issue, there are several other issues involved in the development of a dynamic simulation capability to model dynamic behavior of mechanisms involved in the material handling operations in WALKTHRU. Theoretical aspects of such a dynamic behavior modeler will be discussed in the next chapter.

CHAPTER 4

DYNAMIC BEHAVIOR MODELER

As mentioned in the previous chapters, the development of MTMP is envisioned in WALKTHRU, and a dynamic behavior modeler is a major component of the MTMP system. It has also been stated that one of the primary objectives of this thesis is to develop the theoretical aspects of such a dynamic behavior modeler for mechanisms involved in material handling operations. The scope of this thesis, however, does not encompass the implementation of the dynamic behavior modeler in WALKTHRU. This is basically due to a significantly long time period required to modify the binary files of WALKTHRU. But, such a modification process is unavoidable since it is a must to simulate the motion of objects by the physical principles of dynamics governing the motion to guarantee a satisfactory realism in modeling of construction operations involving material handling equipments (such as mobile cranes) as well as robots which have a significant potential for application.

Stringent technological problems, increasing demands for more sophisticated equipments, and increasing need to visualize real-life performance have generated a growing interest in the development of reliable approaches for the dynamic simulation of systems.

There has been a steadily-increasing interest in "self-formulating" generalized computer based programs which can simulate a broad range of mechanical systems such as vehicles, manipulators, etc. (Richard et al. 1986). The spectrum of desired capabilities in a general-purpose dynamic design problem is very large -- i.e., large element library, static, free vibration and transient response analysis, nonlinear analysis, use of composite materials, design for a variety of objective functions and constraints, and efficient pre- and postprocessing facilities (Rajan and Bhatti 1986).

The general thrust of the dynamic behavior modeler presented in this thesis is *not* to develop a large general-purpose design program with such a wide range of capabilities. The main thrust has been to develop a conceptual dynamic behavior modeler to perform dynamic simulation for computer animation. Such a dynamic simulation capability is essential to accurately model the dynamic response of material handling equipments (such as mobile cranes, robots, etc.) found in construction. The achievement of this thrust ensures realistic visualization and simulation required for efficient and effective multi-tasking motion planning for such equipment.

This chapter provides an insight into the theoretical aspects of a dynamic behavior modeler based on dynamic simulation for computer animation capable of realistically modeling the dynamics of rigid bodies. It is believed that realization of the theoretical model of such a facility will ensure a reliable dynamic simulation and visualization of real-life performance in WALKTHRU. Also, a basis for successful implementation of the MTMP system will be laid. Section 4.2 will present the theoretical aspects of the dynamic behavior modeler envisioned in WALKTHRU. This presentation will encompass the discussion of the strategies and the issues involved in the development of the dynamic behavior modeler in WALKTHRU.

As stated before, the main purpose of this thesis is to provide a means to visualize real-life performance during the motion planning process. This visualization means is the dynamic behavior modeler for mechanisms involved in the material handling operations. Mobile cranes are one of these mechanisms that play a major role in such operations. In addition to the conceptual model of a dynamic simulation capability for computer animation, an analytical model of the dynamics of a load attached to a mobile crane will be presented. The dynamic behavior of the suspended load is modeled with respect to different stages involved in a "pick and place task". Based on this model, the response of the crane's boom to the dynamic loading can be determined. As a sample case, a GL (Graphics Language) program has been written at Virginia Tech to animate the dynamic response of the crane's boom and the dynamic behavior of the load. This program, however, does not perform dynamic simulation for animation. The intent is just to visualize how the conceptually developed modeler would perform. Section 4.3 will describe the sample pick and place task.

First section of this chapter offers a brief insight into basic concepts of dynamics -- dynamic loading, dynamic system and dynamic behavior analysis, before discussing the dynamic behavior modeler.

4.1 Review of Basic Dynamic Behavior Concepts

This section starts with describing a dynamic load, and differentiating between a dynamic loading case and a static loading case. Any load where the magnitude, direction or position varies with time is dynamic. Similarly, the response to a dynamic load, that is the resulting deflections and stresses, vary with time. These loads and responses can be harmonic (such as would result from rotating equipment); complex (such as combination of several harmonic loads); impulsive loads (such as collisions, impacts, or other short-term loads); or random loads (such as earthquake) (Shapiro 1980).

A dynamic problem differs from its static loading counterpart in two important respects. The first difference is the time varying nature of the dynamic problem. Since the load and the response vary with time, it is evident that a dynamic problem does not have a single solution, as a static problem does. A dynamic problem has a series of solutions represented by an equation with time as an independent variable or by values at each time of interest.

However, a more fundamental difference exists between dynamic and static situations. Under static loading, the external loads on a structure are in equilibrium with the moments and elastic forces developed within the structure. If a simple beam is subjected to a static load *p*, as shown in Figure 4.1(a), its internal moments and shears and deflected shape depend directly upon the given load, and can be computed from *p* by established principles of force equilibrium. On the other hand, if the load *p*(t) is applied dynamically, as shown in Figure 4.1(b), the time-varying external loads induce accelerations and displacements in the structure and the ensuing time-varying inertial forces also enter into equilibrium

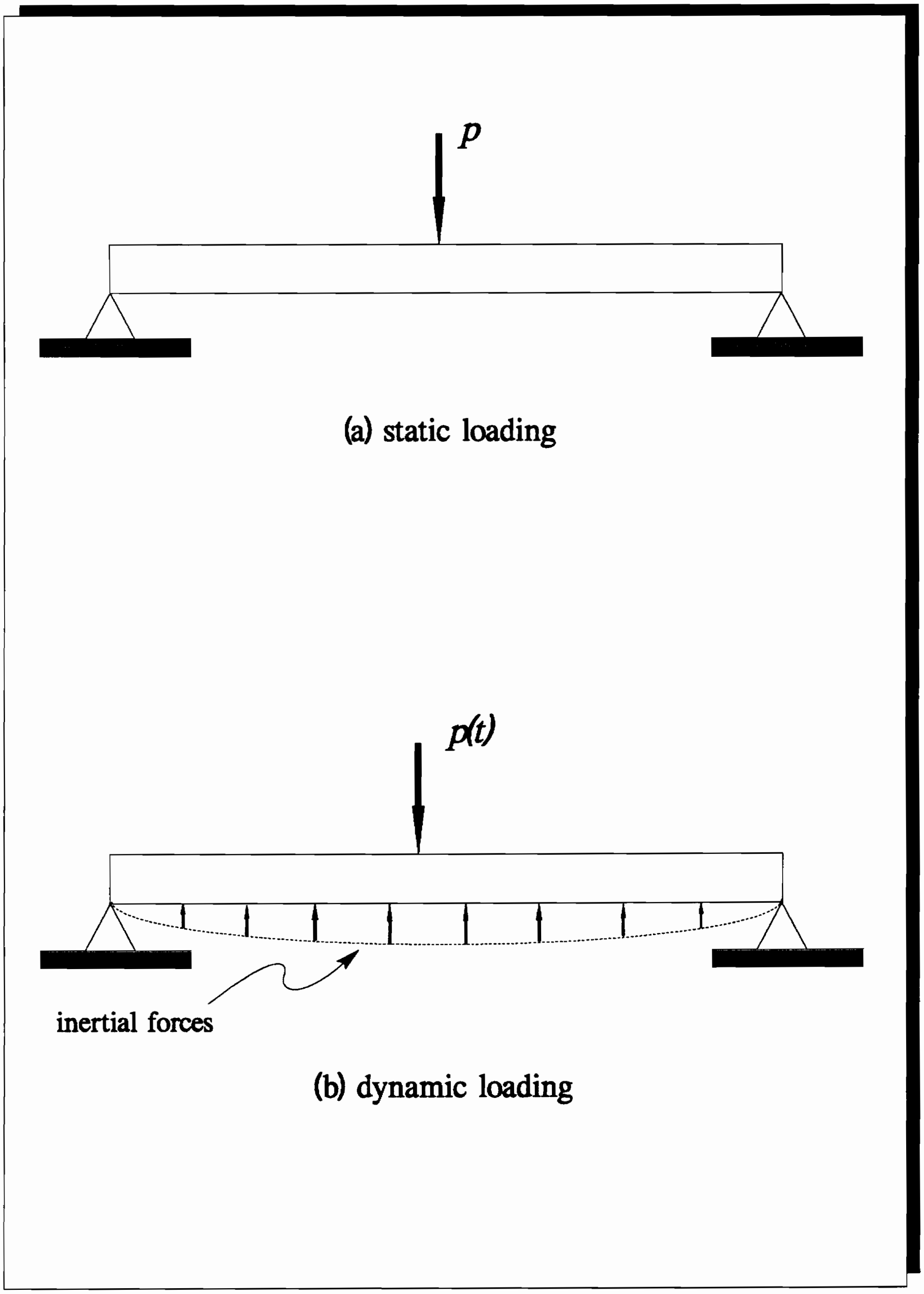


Figure 4.1: Difference Between Static and Dynamic Loads
(Clough and Penzien 1975)

equation. Thus, the internal moments and shears must equilibrate not only the externally applied force but also the inertia forces resulting from the accelerations of the beam.

This section has reviewed the basics of dynamic loading, and now looks at the basics of a dynamic system and dynamic behavior analysis. A dynamic system can be viewed as a multi-body system. It is assumed to be composed of mass particles and rigid bodies interconnected with various common elements such as externally applied forces, torques, springs and dampers which may be hinged to fixed or moving displacement drivers. Moreover, the three-dimensional system may also be subjected to a wide variety of translational or rotational geometric restrictions.

In a dynamic environment, physical objects interact with each other and with the environment that they inhabit. Hence, in such an environment, not only the motion of an object but its relationship with the forces that produce motions is studied. The inertial and physical properties of objects should be defined by a dynamic environment with forces, constraints, structural elements, controls -- everything needed to define the system. As a result, an accurate model of the dynamic behavior helps predict the displacements, velocities, accelerations, and reaction forces due to the inertial and external forces. The following section offers a brief review of concepts involved in dynamic behavior analysis of structures or mechanisms.

4.1.1 Basic Concepts of Dynamic Behavior Analysis

Dynamic analysis evaluates forces, moments, time response, and natural frequencies in systems undergoing time-varying forces. Basically, there are two different approaches for analyzing response to dynamic loads: deterministic and nondeterministic. The choice of method to be used in any given case depends on how the loading is defined (Clough and Penzien 1975).

If the time variation of loading is fully known, even though it may be oscillatory or irregular in character, it is referred as a prescribed dynamic loading; and the analysis of the response of any system to a prescribed dynamic loading is defined as a deterministic analysis. On the other hand, if the time variation is not completely known but can be defined in a statistical sense, the loading is termed a random dynamic loading; a nondeterministic analysis is the analysis of response to a random dynamic loading (Clough and Penzien 1975). In this thesis, the analytical development of the dynamic model of the mobile crane follows the methods of deterministic dynamic analysis.

In general, the response to any dynamic loading is expressed in terms of the displacements of the structure. Thus, a deterministic analysis leads to a displacement-time history corresponding to the prescribed loading history. Other aspects of the deterministic response, such as stresses, strains, internal forces, etc. are usually obtained as a secondary phase of the analysis, from the previously established displacement patterns.

From an analytical standpoint, it is convenient to divide prescribed (deterministic) dynamic loading into two basic categories, periodic and nonperiodic (Clough and Penzien 1975). Some typical forms of prescribed loadings and examples of situations in which such loadings might be developed are shown in Figure 4.2.

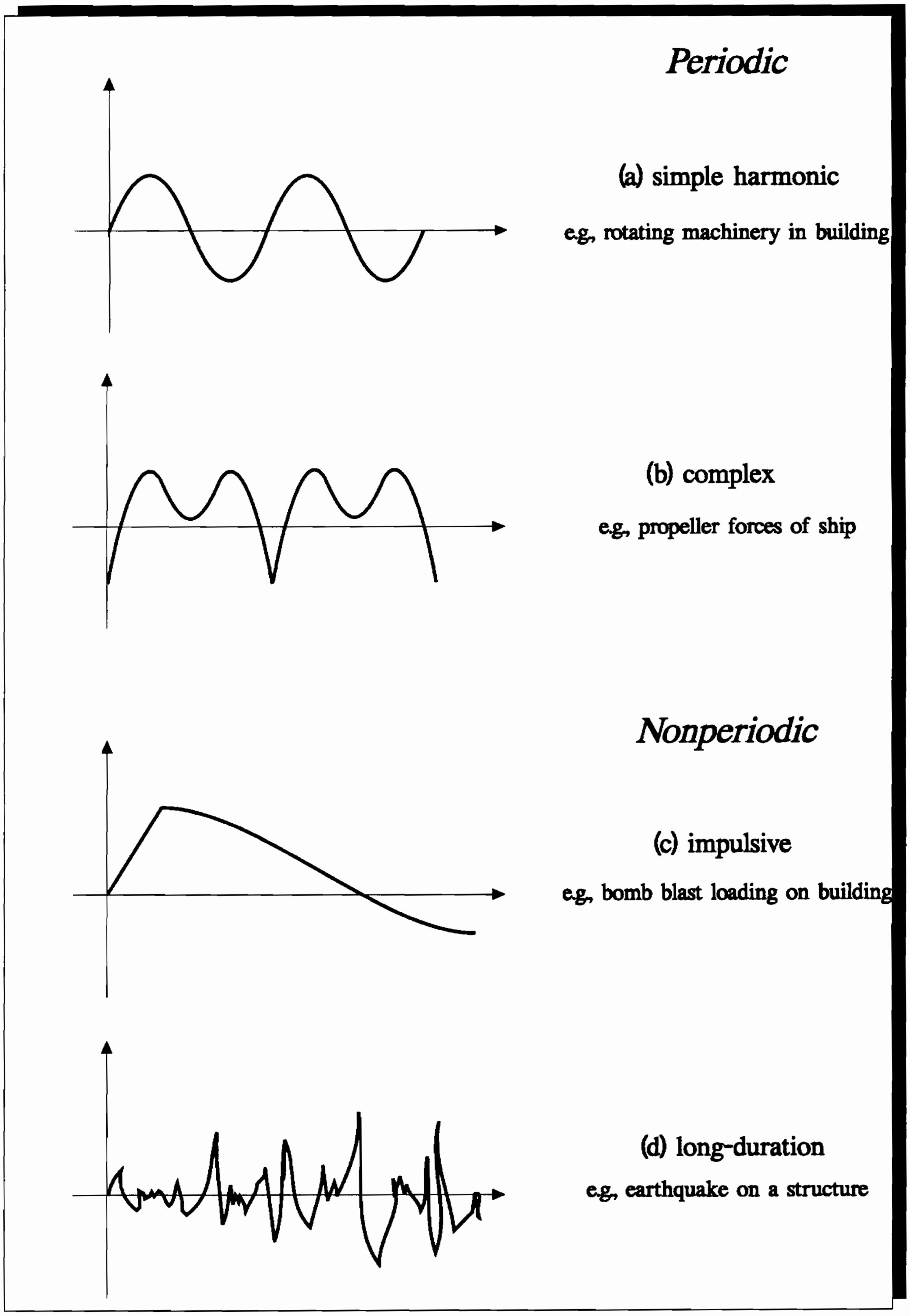

Periodic
(a) simple harmonic
e.g, rotating machinery in building
(b) complex
e.g, propeller forces of ship
Nonperiodic
(c) impulsive
e.g, bomb blast loading on building
(d) long-duration
e.g, earthquake on a structure

Figure 4.2: Characteristics of Typical Dynamic Loadings (Clough and Penzien 1975)

As illustrated in Figures 4.2(a) and (b), periodic loadings are repetitive loads which exhibit the same time variation successively for a large number cycles. The simplest periodic loading is the sinusoidal variation shown in Figure 4.2(a), which is termed *simple harmonic.*

Nonperiodic loadings may be either short-duration *impulsive* loadings or long-duration general forms of loads. A blast or explosion is a typical source of impulsive load, whereas an earthquake is a typical source of long-duration nonperiodic loading. The nonperiodic loadings are shown in Figures 4.2(c) and (d).

A brief review of the basic dynamic behavior concepts are of significant help in understanding the derivation of equations of motion. The equations of motion and their solution are major elements in analytical development of the mobile crane dynamics (discussed in Section 4.3) and dynamic simulation for computer animation. The dynamic simulation issue is discussed in the following section which presents the theoretical aspects of the dynamic behavior modeler.

4.2 Conceptual Dynamic Behavior Modeler

In this section, theoretical aspects of a dynamic behavior modeler based on dynamic simulation for computer animation are presented. Provided with a dynamic simulation capability, it will be possible to implement a dynamic behavior modeler into WALKTHRU which helps to better plan, model, and control the material handling operations involving cranes and robots. It has been stated before that such a capability is also a requirement for the development of the MTMP system.

The specification of motion for computer graphic sequences has traditionally been controlled explicitly by an animator. Also, objects in a scene are looked upon as geometric shapes devoid of dynamical properties. The result is that the animator is forced to use his/her intuition about the physical world in planning the motion of objects in the scene (Hahn 1988). However, motion occurs in the physical world due to forces acting on objects which have shape and mass. There is a need to think of objects in a scene as real objects having mass, moment of inertia, elasticity, friction, etc. To achieve a satisfactory degree of realism, the motion of objects must be simulated by the physical principles of dynamics governing the motion.

There are good reasons that this is a difficult task. The mathematical principles governing the motion of objects are both complex and computationally time consuming. Perhaps, establishing some intuitive link between the parameters of a dynamic simulation and the resulting motion is even more difficult. For example, it is clear that to pick up an object one must move his/her hand from its current position to the object. It is much more difficult to describe the same motion through dynamics, i.e., as a series of forces and torques on joints of a skeletal structure. However, the simulation must have its roots at this level.

The term 'simulation', rather than 'animation' denotes a shift in control from the animator to the underlying physics of the environment. One would like a system for specifying motion which combines the realism of dynamic simulation without removing control from the animator.

The dynamic behavior modeler envisioned in this thesis has been conceptualized to perform dynamic simulation on mechanisms, such as cranes and robots that are or can be involved in material handling operations in construction. And it is important to note that these mechanisms, characteristically are composed of links and joints. In addition to performing dynamic simulation for computer animation, the conceptual modeler contains three means for achieving control. These means are:

1- The imposition of 'kinematic constraints' permits traditional animation systems to be embedded within a dynamic analysis. Motion of portions of an object can be explicitly specified while allowing the remaining sections of the body to react to the dynamic forces created by this motion. Joint limits are also handled in a coherent means through kinematic constraints.

2- The ability to define 'behavior functions' allows the object to react to its surroundings. Behavior functions relate the momentary state of the dynamic system to desired forces and accelerations within the object.

3- A process of 'inverse dynamics' provides a means of determining the forces required to perform a specified motion. Thus, a previously specified action can be transformed into equivalent forces for development of behavior functions or evaluation of stresses within linkage.

The above strategies to provide control without disrupting the dynamic integrity of the resulting motion.

The following section will provide a brief background about animation methodologies. The theoretical aspects of the dynamic behavior modeler will be described further.

4.2.1 Animation Methodologies

Computer animation methodologies can be characterized as belonging to one of three categories: Keyframe Animation, Procedural Animation, and Dynamic Simulation. These three are further discussed below.

Keyframe Animation

Keyframe animation is derived directly from traditional animation techniques in which the animator specifies what is to appear in each frame and thus explicitly specifies the 'kinematics' or motion of the system. The computer adds efficiency by interpolating 'in-between' frames from user supplied 'keyframes' (Stern 1983). Although this type of system gives almost complete control to the animator, it lacks the tools for creating dynamically correct sequences. The current version of WALKTHRU employs this methodology as its animation strategy.

Procedural Animation

Procedural methods rely on the computer's ability to determine the kinematics based on implicit instructions rather than explicit positions. One class of procedural methods is 'inverse kinematics', where the motion of end links in a chain is specified by the animator, but the motion of interior links is determined algorithmicly (Girard and Maciejewski 1985, Korein and Badler 1982). In Girard and Maciejewski's work some dynamic principles are invoked to enable the object to interact with the ground in realistic ways. Although procedural methods have produced good animations, they often lack dynamic integrity.

Dynamic Simulation

General systems for dynamic simulation of linked mechanisms have been described in the literature relating to robotics and biomechanics as well as computer graphics. Wilhelms and Barsky (Wilhelms and Barsky 1985) described a system for dynamic simulation without incorporation of kinematic constraints and the associated control strategies. Armstrong and Green (Armstrong and Green 1985) also described a system based on an alternative dynamic formulation. Williams and Seirig (Williams and Seirig 1979) developed a system for simulating dynamic systems in order to study optimizing strategies for actuator forces. Development of robot machines through simulation relies heavily on similar principles. Experiments reported by Raibert (Raibert 1984) of hopping and running machines reinforce the need for dynamic simulation methods. Witkin et al. (Witkin et al. 1990) aimed to use physical simulation as an interactive medium for building and manipulating a wide range of models. They presented a mathematical and computational formulation for constrained dynamics to achieve their goal. Schroder and Zeltzer (Schroder and Zeltzer 1990) implemented an algorithm for rigid body dynamics which unifies the advantages of linear recursive algorithms with the advantages of earlier linear algebra based constraint force approaches.

As the study of the background and the review of literature reveal, a dynamic simulation capability is essential to visualize the physical environments realistically. There has been a fair amount of research to perform dynamic simulation of 3-D motions of rigid bodies. Although similar in concept, the major difference between the various methods is basically the approach as how to formulate and solve the equations of motion. In addition, the research so far has only dealt with the dynamic motion aspect of the dynamic behavior. However, the displacements due to dynamic loading should also be considered in computer animation.

Another outcome of the literature review is that there is a significant need to model dynamic behavior of mechanisms such as cranes and robots involved in material handling operations in construction. In this thesis and research, a dynamic behavior modeler is conceptually developed to be implemented in WALKTHRU. This modeler, based on dynamic simulation for computer animation is capable of realistically modeling dynamic behavior (not only the motion but the displacements as well) of such mechanisms. In the future, when it is embedded in the MTMP system, this facility is believed to contribute significantly to the realistic visualization, and better planning and modeling of material handling operations in construction. The following section describes the theoretical aspects of dynamic behavior modeler based on dynamic simulation.

4.2.2 Overview of the Dynamic Behavior Modeler

As stated earlier, this thesis's major concern is to conceptually model a system to perform dynamic simulation for computer animation. This section gives an overview of the dynamic behavior modeler developed theoretically to simulate the dynamics of the mechanisms involved in the material handling operations. The overview of such a dynamic behavior modeler is illustrated in Figure 4.3.

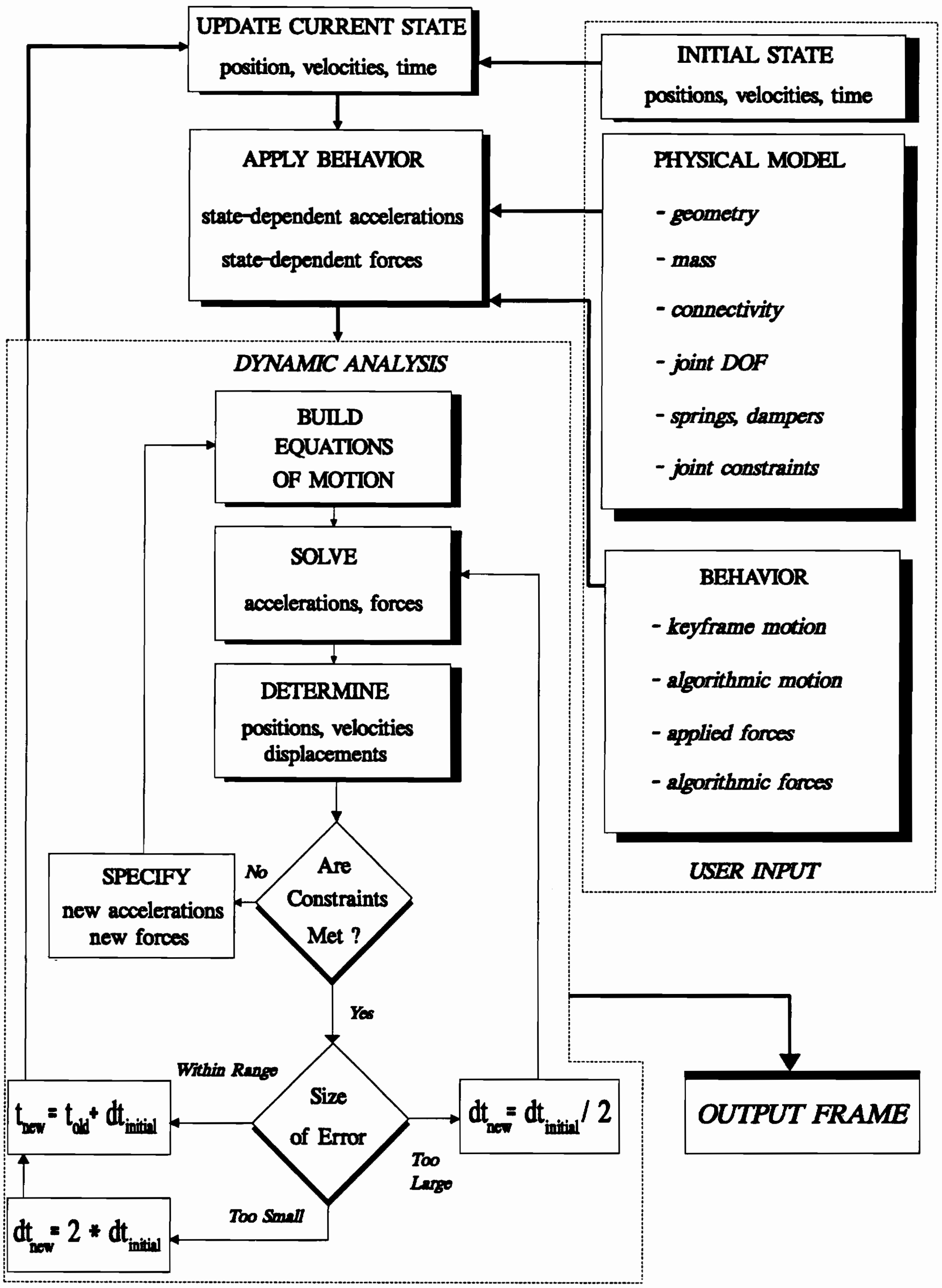


Figure 4.3: Flow of Control for the Dynamic Behavior Modeler

The dynamic behavior modeler envisioned by this thesis requires as input the physical and behavioral characteristics of a linked object placed in an initial state. The physical model includes descriptions of all links and joints, as well as their connectivity. The initial state of the system contains the starting position and the velocity of the links and an initial time. Behavior functions relate the current state of the system to external forces or to specified motion.

The dynamic simulation is treated as an explicit time series analysis. A simultaneous solution is performed at each time increment for the accelerations of each degree of freedom of the dynamic system. These accelerations are integrated with the current state to determine a new set of positions and velocities. The solution is checked to see if any constraints have been exceeded and to see if the accuracy is within a tolerable range. If these tests are passed, the new state becomes the current state and the process is repeated for the following time increment. Time increment corresponding to frame times are recorded for display and playback.

The following sections will discuss the issues involved in the modeler in more detail. These issues mainly are: (1) links, joints and forces, (2) dynamic simulation, (3) kinematic constraints and inverse dynamics.

4.2.3 Links, Joints and Forces

Each link has size, shape and mass and, thus, a center of gravity and moments of inertia. (These are computed by the strategy described in Chapter 3). The linkage for each figure forms a tree structure. Each link possesses one joint at which it is attached to its parent link and may possess one or more joints at which child links are attached. Links move relative to each other via one to six translational or rotational degrees of freedom, associated with each joint.

A key to dynamically creating virtual physical objects lies in the proper treatment of joints. Joints provide the glue that combines simple objects to form complex ones. There are several types of joint, as shown in Figure 4.4. Each of them has different kinematic constraints. Each joint may have associated springs and/or dampers which act to exert internal forces or torques within that joint. Joints may also have associated limits which act to keep the degrees of freedom from moving beyond some point, e. g., the boom of a crane can rotate only within a defined arc about the base of the crane. Joint limits for translation and rotation are illustrated in Figure 4.5.

In addition, the linkage responds to externally applied forces. External forces can be specified as applied torques, point vector forces, or force fields.

The links, joints, forces, and position and the velocity of the degrees of freedom form a complete description of the state of the dynamic system at any given time.

The physical model component of the input in Figure 4.3 (p. 86) can be envisioned within a generic data model for dynamic system modeling, simulation, and graphical animation. Such a model serves as a basis for integrating CAD/CAE and visualization systems. Chapter 5 will present the theoretical aspects of such a data model for WALKTHRU in more detail.

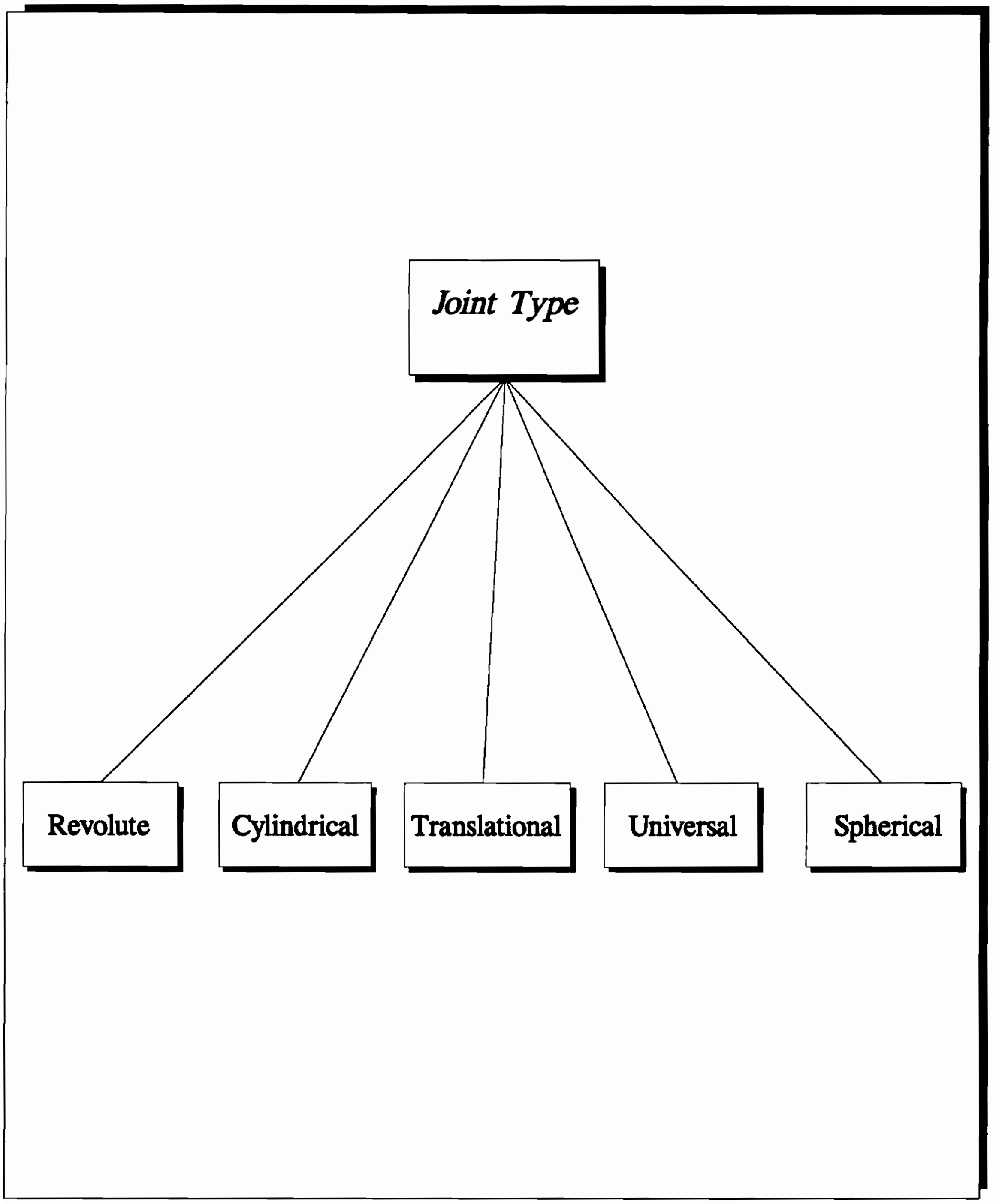


Figure 4.4: Joint Types

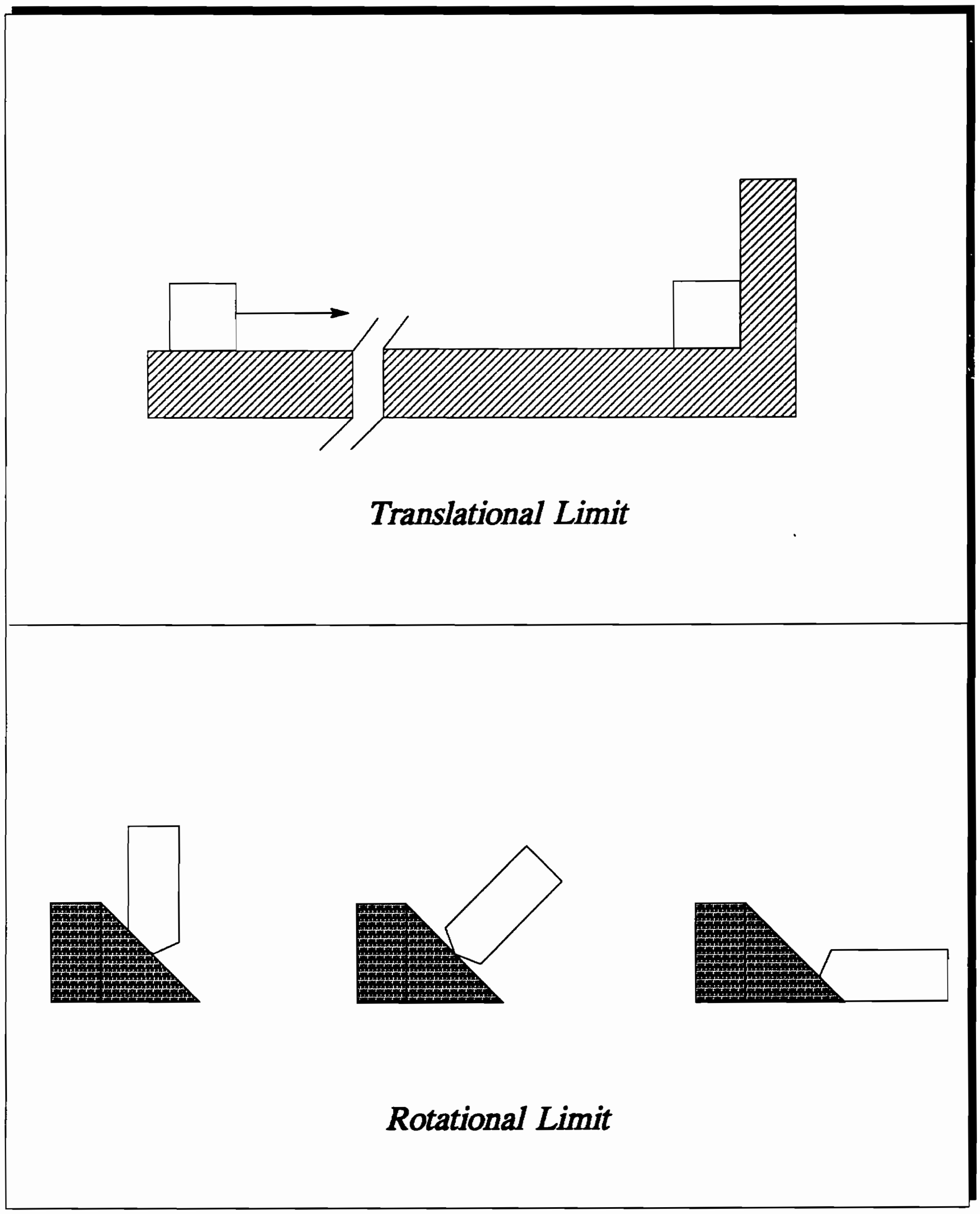


Figure 4.5: Joint Limits

The following section will look at the dynamic simulation issue which is essential for computer animation and central for the dynamic behavior modeler.

4.2.4 Dynamic Simulation

The dynamic simulation within the dynamic behavior modeler can be broken down into four phases for each time increment. These are: (1) execution of the behaviors, (2) calculation of joint forces, (3) formation of the equations of the motion, and (4) matrix solution and evaluation of results.

4.2.4.1 Execution of Behavior Functions

Behavior functions determine, at each moment, forces acting on a linkage and/or specific motion which is to occur. The forces or specified motion can be determined through any algorithm of the user's choosing, based on currently available information about the state of the system (e.g., time, geometry). The user-defined behavior algorithms can be obtained through analytical modeling of the objects' dynamics. The forces or torques involved in this model may be various, such as externally and internally applied, centripetal, coriolis, and coupling. Examples of useful input and associated output for behaviors are shown in Figure 4.6.

A behavior function's output can specify a single force or a force field such as gravity. Gravity's simple behavior function always exerts a downward force equal to the mass times the acceleration of gravity with its point of action at the center of gravity of each link.

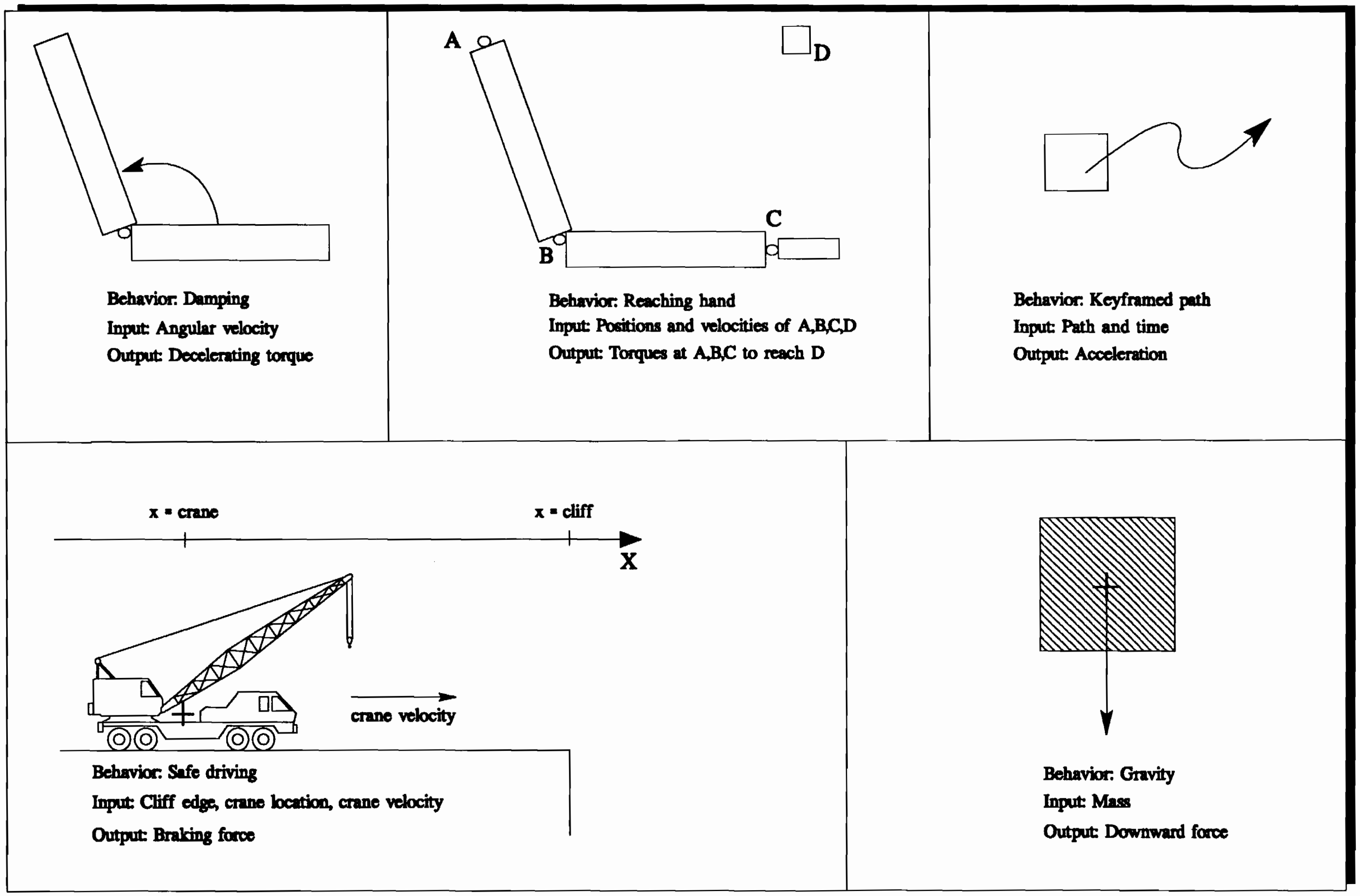


Figure 4.6: Some Sample Behaviors

Contributions from all external forces are summed for each link into an aggregate force and torque vector expressed in the global or 'inertial' spatial frame.

Motion may also be output from a behavior function using time or other input parameters. The specified motion can be defined by keyframed paths which depend only on time, or by procedural means which may depend on other criteria.

The user-designed behavior algorithms can make decisions in virtually any way, ranging from "begin the keyframed motion of the mechanism when the starting gun sounds" to "apply torques to all motors that will lift the boom". In addition, these algorithms may be nested; thus one behavior function may invoke others, allowing for higher level behaviors such as moving the crane with a pendulating load.

The mixture of specified forces and specified motion expressed through the behavior functions provides the combination of kinematic control and dynamic integrity.

4.2.4.2 Calculation of Joint Forces

Given the current positions of the degrees of freedom, internal spring and damper forces are calculated through the equations:

$$F\ (\text{spring}) = k\ (\text{spring}) * dl \qquad (4\text{-}1)$$

$$F\ (\text{damper}) = k\ (\text{damper}) * v\ (\text{DOF}) \qquad (4\text{-}2)$$

where k (spring) and k (damper) are the spring and damper constants for that degree of freedom, dl is the offset from center position, and v (DOF) is the velocity of that degree of freedom. These equations are used for both translational and rotational degrees of freedom. The resulting forces are summed into internal force and torque vectors for each joint.

4.2.4.3 Building the Equations of Motion

At this stage all physical parameters have been determined. Thus, each object may be regarded as a passive linkage moving in response to applied loads. The links and joints of an object have a given position and velocity, and they are subjected to internal and external forces. The primary unknowns are the momentary accelerations of the degrees of freedom (q").

A linear equation can be derived for each degree of freedom relating the current state of the object and the accelerations it undergoes to the forces which are acting on it. (Equations relating to degrees of freedom with accelerations pre-specified by the behavior functions are eliminated. This is described in Section 4.2.5). The simplest view of this relationship is Newton's second law, that force equals mass times acceleration. The series of equations can be written:

$$|A|\,|q''| = |B| \qquad (4\text{-}3)$$

where: $| A |$ is a generalized mass matrix.

$| q'' |$ is a vector of the accelerations of each of the degrees of freedom.

$| B |$ is a vector of force terms.

The $| A |$ matrix coefficients are dependent only on the geometry and mass of the system. This includes the current configuration of all joints and links as well as the mass and moments of inertia of the links. The $| B |$ vector includes terms for all applied forces as they relate to each degree of freedom.

Among the numerous texts on dynamics of systems of rigid bodies, Wittenburg (Wittenburg 1977) has been found to be of the most use in the conceptual development of the dynamic behavior modeler. A derivation for the equations of motion is presented in Appendix C.

4.2.4.4 The Equations Solution

There are several approaches as how to solve the equations of motion. Efficient recursive schemes have been devised to replace the simultaneous equation solution which is the strategy proposed within the dynamic behavior modeler. The recursive solutions have been shown efficient for the determination of motion from specified forces (Featherstone 1983) or for finding actuator forces required to execute specified motion (Schroder and Zeltzer 1990). In addition, an iterative approach to approximately solve the equations of motion introduced by van Overveld (van Overveld 1991) seems to be a simple and efficient solution.

However, these solutions do not allow the combination of partial force and partial motion specification within the same link. This combination permits the control that is central to the dynamic behavior modeler presented in this thesis. This control can be achieved by forming the set of simultaneous equations and solving it for each time increment. A simple Gaussian elimination scheme can work well. The remainder of this section describes the proposed strategy to form and solve the equations of motion.

The solution provides the accelerations of the degrees of freedom for the current time increment. From these accelerations and the current position and velocity of each degree of freedom, new positions and velocities are calculated for the following time step. If constraints are exceeded during the time increment, their constraining accelerations are determined and explicitly specified, the constrained degrees of freedom are removed from the system, and the time increment is repeated.

The size of the time increment is crucial to the accuracy and stability of the simulation since the geometric terms are assumed to remain constant throughout a time increment. If the geometry is changing rapidly, this assumption can quickly lead to inaccurate solutions. To overcome this problem without overburdening the machine by enforcing very small time increments, an adaptive time step sequence is introduced, as shown in Figure 4.3 (p. 86).

A variation on a 'predictor corrector' method (Conte and de Boor 1980) allows the time step to vary based on momentary conditions of the stability of the equations. A starting sequence is achieved by more expensive 'Runge-Kutta' methods for the initial three time increments to provide a history for following time steps. After the initial time increments, predictions for the positions and velocities of the degrees of freedom are made for the following time step based on recent past history through a polynomial extrapolation. The equations of motion are then formed from these "predicted" results and solved to find new accelerations for the same time step. The new accelerations are interpolated with past accelerations and integrated to find "corrected" results for the positions and velocities. If the predicted positions agree sufficiently with the corrected results, then the time step is held constant. If they do not coincide, then the results are thrown out and the time increment is halved and repeated. If the agreement is very good, the result is kept and the increment is doubled for subsequent time steps. In this way the size of the time increment adapts to changing conditions throughout the simulation. At no time is the time increment allowed to exceed a frame time, i.e., 1/24th of a second. Results from time increments representing frames are recorded for later playback.

4.2.5 Kinematic Constraints and Inverse Dynamics

Solving an equation when the forces are given is called Forward Dynamics. On the other hand, solving for forces when the accelerations are given can be called Inverse Dynamics. Since it is often difficult to think of motion in terms of the given forces, a system capable of performing both forward and inverse dynamics is desirable.

Equation 4-3, simply stated, is a relationship between geometry, acceleration, and forces. If all the values of matrix $| A |$ are known, then there are two ways to view the situation. The force vector, B, can be specified and solved for the resultant accelerations:

$$q'' = | A |^{-1} B \qquad \text{(4-4: Forward Dynamics)}$$

or in the simpler case, the acceleration vector, q", (i.e., kinematic constraints) can be specified, and the forces which would cause such an acceleration can be determined:

$$B = | A | q'' \qquad \text{(4-5: Inverse Dynamics)}$$

4.2.5.1 Kinematic Constraints

A kinematic constraint consists of an explicit specification for the acceleration of some degree of freedom during the current time increment, thus removing an unknown degree of freedom from the system. Kinematic constraints may arise in three ways: (1) they may be prespecified by the animator as part of a prescribed sequence, (2) they may come into effect only when some inequality is satisfied, such as when the maximum rotation of a crane boom joint constraint is exceeded, or (3) they may be invoked by a behavior based on current criteria in the system, (e.g., the load stays above the ground at a certain height until lowered).

Within the context of the mathematical formulation, a kinematic constraint consists of removing a row and a column from the system of equations. As an example, in a system with three degrees of freedom, if the first and third are prescribed through kinematic constraints:

$$\begin{bmatrix} A_{11} & A_{12} & A_{13} \\ A_{21} & A_{22} & A_{23} \\ A_{31} & A_{32} & A_{33} \end{bmatrix} \begin{bmatrix} \ddot{q}_1 \\ X \\ \ddot{q}_3 \end{bmatrix} = \begin{bmatrix} X \\ B_2 \\ X \end{bmatrix} \qquad \text{(4-6: X's unknown)}$$

The unknown degree of freedom, q''_2 can be solved for using the following general method:

(a) For each i where q''_i is given, move all terms involving q''_i to the right side by subtracting from the force vector the product of q''_i and the ith column of the | A | matrix.

$$\begin{bmatrix} 0 & A_{12} & 0 \\ 0 & A_{22} & 0 \\ 0 & A_{32} & 0 \end{bmatrix} \begin{bmatrix} \ddot{q}_1 \\ X \\ \ddot{q}_3 \end{bmatrix} = \begin{bmatrix} X \\ B_2 \\ X \end{bmatrix} - \begin{bmatrix} A_{11} \\ A_{21} \\ A_{31} \end{bmatrix} \ddot{q}_1 - \begin{bmatrix} A_{13} \\ A_{23} \\ A_{33} \end{bmatrix} \ddot{q}_3 \qquad (4\text{-}7)$$

(b) Remove the rows and columns for each equation, i, for which an acceleration, q''_i is prescribed.

$$[A_{22}]\ [X] = [B_2] - [A_{21} * \ddot{q}_1] - [A_{23} * \ddot{q}_3] = [B_2\ \text{new}] \qquad (4\text{-}8)$$

(c) Solve the reduced system for the unknown acceleration, q''_2.

$$[\ddot{q}_2] = [A_{22}]^{-1}\ [B_2\ \text{new}] \qquad (4\text{-}9)$$

It is important to note that the new acceleration found by this method is in a sense, a response to the given ones. This is because in step (a), for each degree of freedom with a prescribed force, a reactant force to the given accelerations is added to the original force. Hence, the solved motion is reactant to the prescribed motion.

The specification of some portion of an object's motion leaves the remaining degrees of freedom free of respond to the constrained motion under the control of dynamic simulation. The ability to prespecify some motion within a dynamically based model provides the animator with the power of dynamic simulation while maintaining the control found in traditional animation methods. Thus, keyframe techniques can be embedded within a dynamic simulation system. If all parts of the body are constrained then there are no unknowns and the system reverts completely to a traditional animation system.

4.2.5.2 Inverse Dynamics

Continuing with the above example, once the unknown degree of freedom acceleration has been found, the unknown forces can be found from the newly computed accelerations through inverse dynamics.

(a) Substitute the new-found acceleration (q''_2) into the original Equation 4-6.

(b) For each degree of freedom, i, with q''_i originally given, multiply row i of $| A |$ by the acceleration vector to find B_i new, the unknown force.

A specific desired motion can thus be converted to the equivalent set of forces. In the original formulation of Equation 4-3, values are found for B_i of all degrees of freedom. These original B_i contain all known internally and externally applied, centripetal, coriolis, and coupling forces. This knowledge can be used to an advantage, if:

$$B_i \text{ new} - B_i = F_a \qquad (4\text{-}10)$$

for the degrees of freedom with prescribed motion. F_a is then the additional force that a motor would have to exert on that degree of freedom to bring about the prescribed q''_i. For example, this permits the determination of robot actuator forces needed to perform a specified task.

The ability to mix forward and inverse dynamics has two direct implications for animation purposes. First, a keyframing animation system, such as the one in WALKTHRU can be embedded within a dynamic system. The key visual elements of a sequence can be programmed by keyframing them while allowing the other elements to react to them. Secondly, knowledge of an actuator force can greatly increase the ability to develop behavior functions.

Sections 4.2.1 through 4.2.5 has presented the theoretical aspects and the strategies involved in the dynamic behavior modeler. The following section will provide a summary and conclusion while emphasizing the contributions of such a modeler.

4.2.6 Summary and Conclusion

The theoretical aspects of a system to model dynamic behavior of linked mechanisms (such as cranes, robots) that can be involved in material handling operations in construction has been presented. The definition of the mechanisms includes behavioral as well as physical characteristics. The behaviors cause the mechanisms to react to their momentary state through the imposition of external and/or internal forces and/or torques or through explicit specification of motion. The formulation of the equations of motion permits the imposition of kinematic and limiting constraints on the unknown degrees of freedom associated with each joint. An inverse dynamics procedure evaluates the equivalent force(s) which would be required to create the same motion as that specified by kinematic constraints. The dynamic simulation is run as an explicit time series analysis with predictor corrector methods maintaining accuracy and efficiency in the solution.

The behaviors, kinematic constraints, and inverse dynamics which were introduced in this chapter provide control mechanisms to achieve a desired motion while maintaining dynamic integrity throughout the simulation. The dynamic behavior modeler with such control mechanisms is capable of performing dynamic simulation for computer animation.

The scope of this thesis does not include the implementation of the dynamic behavior modeler. This is due to a significant time period required to modify particular files and create new ones within WALKTHRU. However, in Chapter 5 the issues that are involved in such an implementation are discussed in detail within the context of a data model.

As stated before, the dynamic behavior modeler is envisioned to be a major component of a multi-tasking motion planning (MTMP, presented in Chapter 2) system for the material handling operations in construction. The primary aim of MTMP is to better plan, model, and control such operations.

Within the context of MTMP, the major contribution of the dynamic behavior modeler is its capability to provide a satisfactory degree of realism in the visualization of the material handling operations. Such a capability ensures the reliability of the MTMP system. So far, there has not been a system which takes into account the dynamic behavior of mechanisms during motion planning.

The dynamic behavior modeler will let the engineers animate the material handling operations during the design and planning phase of the constructions projects. The realistic and reliable visualization provided through the dynamic behavior modeler will enable engineers to better plan, model, and control such operations. This will lead to significant improvements in productivity, safety, quality, and timeliness of these operations. This will further lead to improvements in constructability by reducing rework and the occurrence of accidents.

In addition, the dynamic behavior modeler will provide significant advances towards application of multi-rigging operations. Extended with a capability to analyze stresses and strains due to dynamic loading, the modeler will ensure proper and safe planning of a multi-rigging multi-tasking environment.

Finally, the dynamic behavior modeler is of significance for the development of a generic data model which serves as a basis for integrating CAD/CAE and visualization systems. The dynamic behavior modeler helps generate the data required for dynamic system modeling, simulation, and graphical animation. Within such a data model, the dynamic behavior modeler not only provides a realistic visualization, but ensures a reliable design evaluation. The data model equipped with the dynamic behavior modeler simplifies the modeling procedure, hence contributes to the improvements in the engineering design process. Chapter 5 will present the data model envisioned in WALKTHRU and its significance for modeling process.

The remainder of this chapter will present a possible scenario for computer animation. The scenario involves the process where a mobile crane picks up a load, transports it, and finally places it down. The dynamic behavior of the load and the response of the crane's boom to the dynamic loading are modeled analytically. The analytical model is a basis to write a GL program to display the dynamic responses of the load and the boom. However, as stated before, this GL program does not perform dynamic simulation for computer animation. It is based on key frame animation; however it can provide an insight into the animation that is supposed to be achieved by the dynamic behavior modeler.

4.3 Sample Case

This section first offers background about the dynamics of cranes. This background includes a review of the research that has been done in this area. Then, a sample case that involves a mobile crane carrying a load will be presented.

4.3.1 Background and Literature Review

"A crane that can move freely about the jobsite under its own power without being restricted to a predetermined travel path requiring extensive preparation" is a mobile crane (Shapiro 1980). A mobile crane is a self-propelled crane common to many construction sites. The mobile has found its greatest utility on the construction site because of its ability to hoist large, heavy loads and to position itself quickly for different tasks (Finn 1982).

The mobile cranes are involved in various material handling operations in construction. Throughout these operations the mobile cranes are subject to external loads as well as internal loads. Normal operating conditions do not produce dynamic loads which can affect the cranes stability. However, rapid acceleration or deceleration of the load caused by an instantaneous release of the load, a sudden application of the brakes during load lowering, or a collision between the load and a structure within the environment can produce dynamic forces that will severely affect the crane's response (Finn 1982). As a result, mobile cranes are subject to dynamic loads during operation, and in some way the effects of these loads must be accounted for realistic motion planning.

There has been a fair amount of research to study the dynamic behavior of several types of construction cranes. However, most of this research has been done in Japan, Russia, and Poland, and unfortunately, a significant portion of the research documentation is in the researcher's own language. Thus, the literature survey presented in this section is limited with the documentation published in English.

Johnson (Johnson 1976) and Ward and Johnson (Ward and Johnson 1978) developed linearized equations of motion for a two-element crane boom using Newton's method. The boom equations are decoupled using a coordinate transformation, thus neglecting the inertial coupling terms. Johnson disregarded the nonlinear pendulation of the load, and elastic backstays, but included nonlinear terms due to large angle rotations.

A rather sophisticated analytical model for a crawler crane has been developed by Patten (Patten 1980). The development includes an elaborate soil model which allows translation and rotation of the crane base, pendulation of the load, rotation of the boom, and nonlinear elastic backstays. The crane boom is modeled as a continuum with three bending modes and rotary inertia. The crane base motion is also modeled to include the effects of tilting. The nonlinear system equations are numerically integrated using the Hamming-Milne predictor-corrector technique.

Finn (Finn 1982) studied the same crawler crane which was modeled by Patten. However, his reduced-order model is simpler than Patten's. Because of its simplicity, Finn's model provides an opportunity to add auxiliary devices to the crane with comparative ease. Also, there is a capability to adapt a feedback control system and actuator for the crane to attenuate the dynamic response induced by adverse loading. This continuous, real-time controller absorbs energy from the system that might otherwise cause the crane to overturn, or induce large stresses in the crane components.

Ito et al. (Ito et al. 1985) studied the forward stability of a truck crane. They proposed an approximate method using a simplified simulation model to analyze the behavior of a truck crane overturning in the direction of the lifted load by sudden stop during load lowering. Thus, they were able to determine the minimum acceptable forward stability of a truck crane. They have also clarified effects of crane specifications and constants on the stability.

Sakawa and Nakazumi (Sakawa and Nakazumi 1985) derived a dynamics model for the control of a rotary crane, which makes three kinds of motion (rotation, load hoisting, and boom hoisting) simultaneously. Their objective was to transfer a load to a desired place in such a way that at the end of the transfer the swing of the load decays as quickly as possible. They first applied an open-loop control input to the system such that the state of the system can be transferred to a neighborhood of the equilibrium state. Then they applied a feedback control signal so that the state of the system approaches the equilibrium state as quickly as possible. The results of the computer simulation showed that the open-loop plus feedback control scheme work well.

Moustafa and Ebeid (Moustafa and Ebeid 1988) developed a non-linear dynamics model for an overhead crane. Their model takes into account simultaneous travel and transverse motions of the crane. Their aim was to transport an object along a specified transport route in such a way that the swing angles are suppressed as quickly as possible. They also developed an antiswing control system which adopts a feedback control to specify the crane speed at every moment. The model and control scheme were simulated on a digital computer and the results showed that feedback control works well.

Jones and Petterson (Jones and Petterson 1988) presented the mathematics describing oscillation damped trajectories for simply suspended payloads using controlled acceleration. They claimed that by properly programming the acceleration of the transporting device (e.g. crane) an oscillation damped transport and swing free stop is obtainable. They implemented their theory using a CIMCORP XR6100 robot.

Hara et al. (Hara et al. 1989) studied on the simulation of a jib crane control strategy which transfers a load under the condition of suppressing the load swing both in the transfer process and at the objective position, making the transfer time as short as possible. They derived a non-linear dynamic equation of the load in a jib crane motion. However, they only worked on the case where the extending or shrinking motion of the boom causes the load swing. After they linearized the equation of motion, they defined a second-order cost function, and solved the control problem by the Pontryagin maximum principle.

The review of the previous work on analytical modeling of crane dynamics reveals that this is indeed a significantly complex task. Hence, the researchers have always introduced approximations and simplifications to the complexity of the mechanisms and mathematics involved. The following section presents a sample pick and place task involving a suspended load transported by a mobile crane. The analytical model of the dynamics of the load and the response of the crane's boom to the dynamic loading for each stage of the sample scenario will be presented in Appendix E.

4.3.2 Sample Pick and Place Task

A pick and place task, in which an object is grasped, raised, moved to the final position, and placed down, may be divided into three phases: (1) raising the object, (2) transport of the object, and (3) placing the object down.

A fundamental requirement of the transport phase is that the object be stationary when the transport is completed. The object can then be lowered without uncertainty about its location when placed down. When the object can be grasped so that it is constrained by the manipulator's end effector (in case of a robot), then the object is certain to be stationary at the end of transport. However, there are some cases (in case of a crane) where objects can not be directly grasped. Objects must be picked up by some type of hook. Transport of the suspended objects will generally result in undesired oscillation, or swinging, of the object.

The purpose of this section is to describe the sample case which is used to analytically model the dynamic behavior of a suspended load and to determine the response of the boom of a mobile crane to the dynamic loading. Both the dynamic behavior of the load and the dynamic response of the boom are discussed for different phases of the pick and place task. The detailed derivation of equations will be provided in Appendix E.

Given a set of crane configurations and initial conditions, the analytical model has been used as a basis to write a GL program which is to display the dynamic behavior of the load and the crane in an animation manner. The source code of the GL program is provided in Appendix F.

4.3.2.1 Description of the Sample Case

The material handling system under consideration can be simplified as shown in Figure 4.7. The transporting device (mobile crane) moves in a horizontal direction (normal to gravity) while the suspended load is free to oscillate (pendulate) about the pivot point O. If the moving pivot point O undergoes a particular acceleration profile, the suspended load will exhibit an oscillation transport and stop.

For simplicity, the following assumptions are made:

- The effects of wind forces are not considered.
- The boom can be regarded as a rigid body, and the load can be regarded as a point mass. The dynamics of the crane body and the soil are not considered.
- Elongation of rope due to tensile forces is neglected.
- The boom is considered as a cantilever beam.
- The angle $\emptyset$ is so small that $\cos\emptyset = 1$, and $\sin\emptyset = \emptyset$.

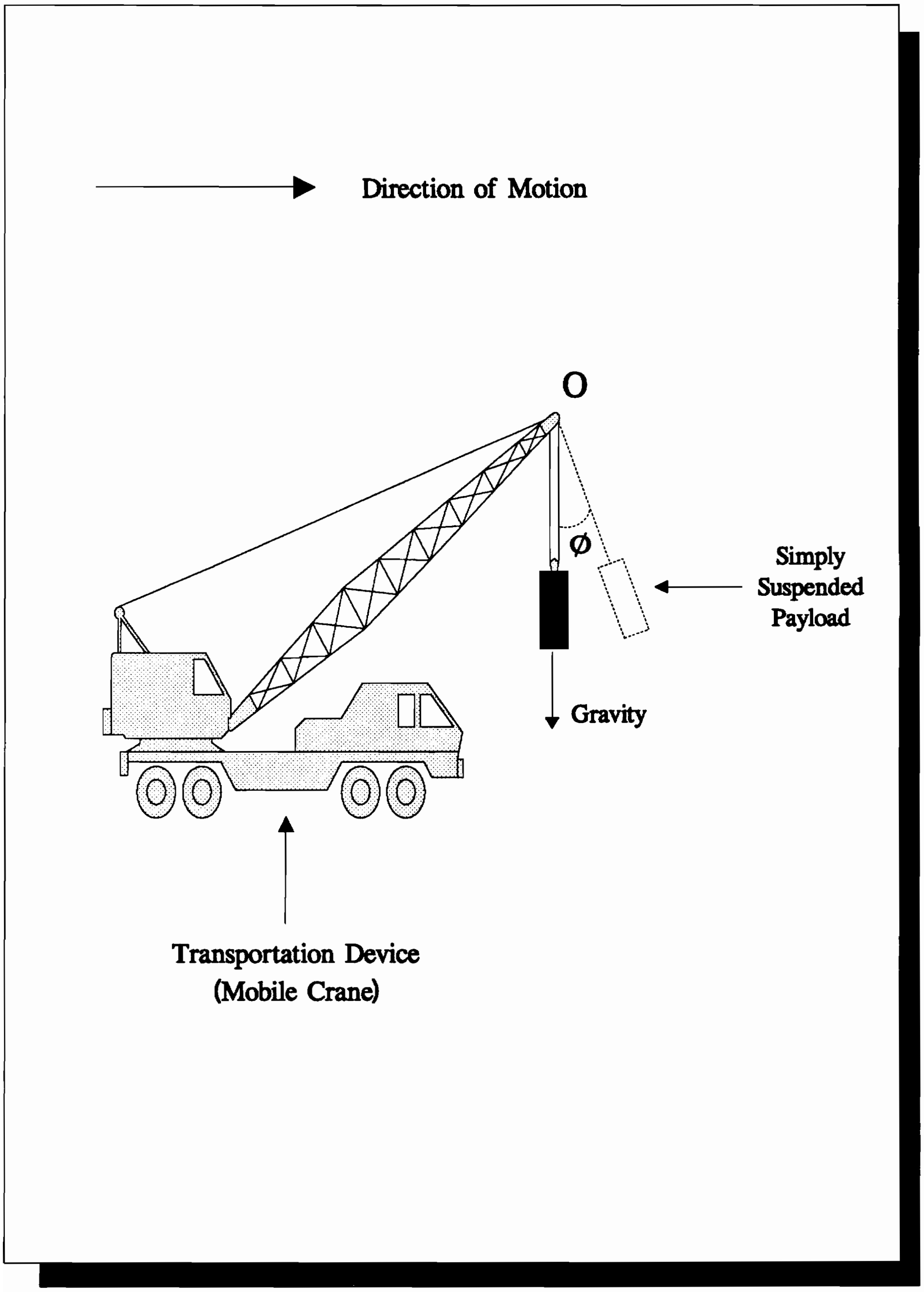


Figure 4.7: Diagram of Transportation System

Figure 4.8 shows an acceleration profile for the moving pivot point O that can result in an pendulating motion for the load. The following scenario is introduced for a sample pick and place operation.

1- Stage 1 in Figure 4.8
   - Boom lowers by 2 meters
   - Load is hooked to the boom
   - Boom lifts by 2 meters
2- Stage 2 in Figure 4.8
   - Crane moves forward 100 meters with positive acceleration
3- Stage 3 in Figure 4.8
   - Crane moves forward 100 meters with no acceleration
4- Stage 4 in Figure 4.8
   - Crane moves forward 100 meters with negative acceleration, and stops
5- Stage 5 in Figure 4.8
   - Boom turns left by 45 degrees
   - Boom lowers by 2 meters
   - Load is unhooked from the boom
   - Boom rises by 2 meters
   - Boom turns right by 45 degrees

The derivation of equations that describe the dynamic behavior of the suspended load and the boom's response to this dynamic loading will be discussed in Appendix E. This discussion will include the presentation of the equations for each stage involved in Figure 4.8.

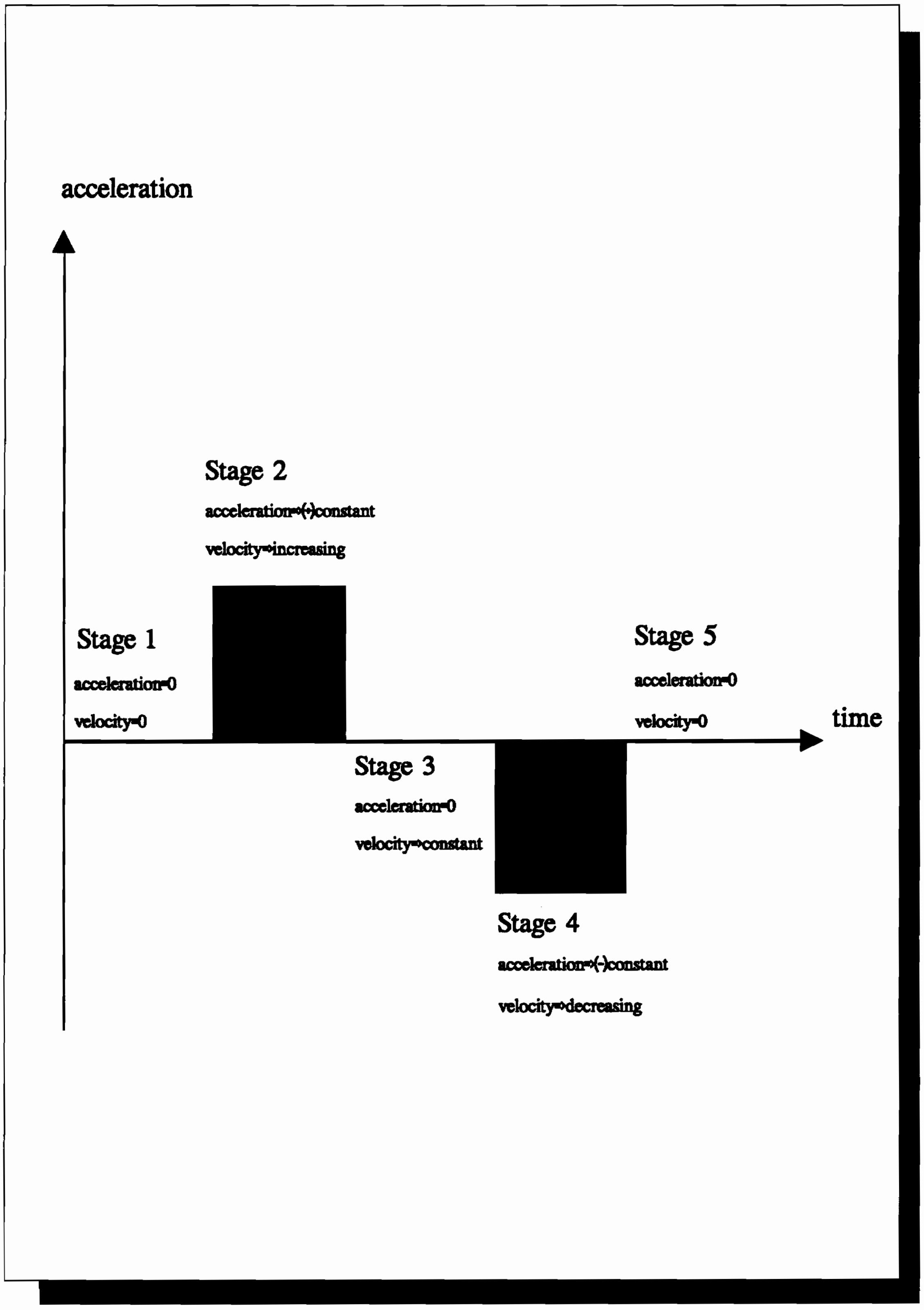


Figure 4.8: Acceleration Profile

The analytical model of the dynamics of the load and the boom has been used to develop a GL program to display the pick and place scenario. Appendix F will provide the source code of this GL program.

CHAPTER 5

DATA MODEL FOR WALKTHRU

"Advanced CAD systems provide engineers with geometric modeling, part assembly, and visualization capabilities" (Wu et al. 1990). Many CAD/CAE systems have been developed to analyze performance of design from different aspects. Such systems are of significant help for engineers in evaluating the overall performance of their design. Simulation and animation packages are undoubtedly among these systems.

There has been some research and development to build an architecture for concurrent design using loosely coupled integration strategy (West Virginia University 1989). Such an architecture can be a basis to integrate various kinds of engineering tool systems for concurrent design to improve engineers' productivity. Each tool system in the integrated system represents a local object workspace. Within a local object workspace, a design model has attributes that are shared with other tool systems. In addition, the design model also has application specific attributes that are used only in the local object workspace. Such commonality and difference are caused by data abstraction (Brodie et al.1984). However, the design models of the same product in local object workspaces are different and can not be derived from other workspaces easily.

Wu et al. (Wu et al. 1990) presented a generic mechanical system data model to integrate CAD/CAE and visualization systems. The contents of the data model are organized in an object-oriented approach. But, the usage of the data model is not limited to object-oriented applications. The data model is developed in a generic fashion such that models for dynamic simulation and animation can be generated. However, the data model was presented in a conceptual level without considering detail implementation factors. In addition, the data model presented in their paper focused on describing the model itself. The attributes for defining the simulation and animation environment are not included in the data model of a mechanical system.

As revealed by the literature review, the integration of CAD/CAE and visualization systems is of significant help in the planning and designing phase to improve engineers' productivity. Such an integration through a data model simplifies the modeling procedure. In their paper, Wu et al. (Wu et al. 1990) indicated that a dynamic behavior modeler is central for such a data model, although they did not develop it.

The conceptual dynamic behavior modeler presented in Chapter 4 is of significance not only in providing a realistic visualization, but also within a data model for design and analysis purposes.

This chapter presents a data model for rigid body dynamic system modeling, simulation, and graphical animation. The data model is based on the model introduced by Wu et al. (Wu et al. 1990). The data model presented in this chapter extends Wu et al.'s model through the incorporation of the attributes for dynamic simulation for animation. Also, this model is organized in such a way to consider the characteristics of WALKTHRU as the visualization system. The combination of such a data model with the dynamic behavior modeler presented in the previous chapter will extend WALKTHRU from a visualization tool to an enhanced simulation and animation package with design and analysis capabilities.

It is believed that WALKTHRU is an excellent potential platform to be integrated with CAD/CAE systems. As mentioned in Section 1.5; besides its simulation and animation characteristics, WALKTHRU is equipped with a capability that enables the transfer of models from several CAD software such as CADAM, CATIA, AutoCAD, etc. However, in order to store and retrieve the physical information about the objects within WALKTHRU, new data structures need to be created. In addition, binary files of WALKTHRU should be modified so as to enable the animation of the dynamic behavior in real time. As mentioned earlier, the scope of this thesis does not include the implementation of this modification and new data structures. The integration of CAD/CAE systems and WALKTHRU can only be achieved if such modifications are performed along with the implementation of the dynamic behavior modeler and the data model.

The data model envisioned in this chapter is a structured description about the mechanisms involved in material handling in construction. Such a model serves as input for modeling, dynamic simulation, and animation. The data model contains the necessary attributes to describe: (1) geometry, (2) assembling information, (3) dynamic simulation model, and (4) visual parameters. The geometry is outlined by polygons. The polygons enclose a region in 3-D space that is an approximation of the region occupied by an object. Such a data model provides three different application views. They are CAD view, dynamic simulation view, and visualization view. Thus, the data model serves as the common basis for describing the model for these different applications (Wu et al. 1990).

The data model serves as a basis for integrating CAD/CAE and WALKTHRU. As shown in Figure 5.1 (Wu et al. 1990), in an integrated CAD/CAE environment, a CAD system and a dynamic system modeler first generate the data model of the mechanisms. The data model is then used to extract the corresponding model for the simulation. Finally, geometric and assembling information derived from the data model and position and orientation data obtained from the simulation results are used for animating dynamic behavior of the mechanisms.

5.1 Data Model

The data model introduced by Wu et al. (Wu et al. 1990) only encompasses the attributes of assembling information and visual parameters involved in the environment shown in Figure 5.1. Section 5.1.1 will look at these attributes.

The conceptual dynamic behavior modeler presented in Chapter 4 is believed to contain the required attributes and generate the required simulation data to be considered as a "dynamic system modeling tool" in the data model. Section 5.1.2 will relate the dynamic behavior modeler with other components in the environment, and discuss the significance of the dynamic behavior modeler for the data model.

5.1.1 Model Definition

The hierarchical structure of the data model of rigid body dynamic system for WALKTHRU is shown in Figure 5.2. The model of such a system is composed of: (1)

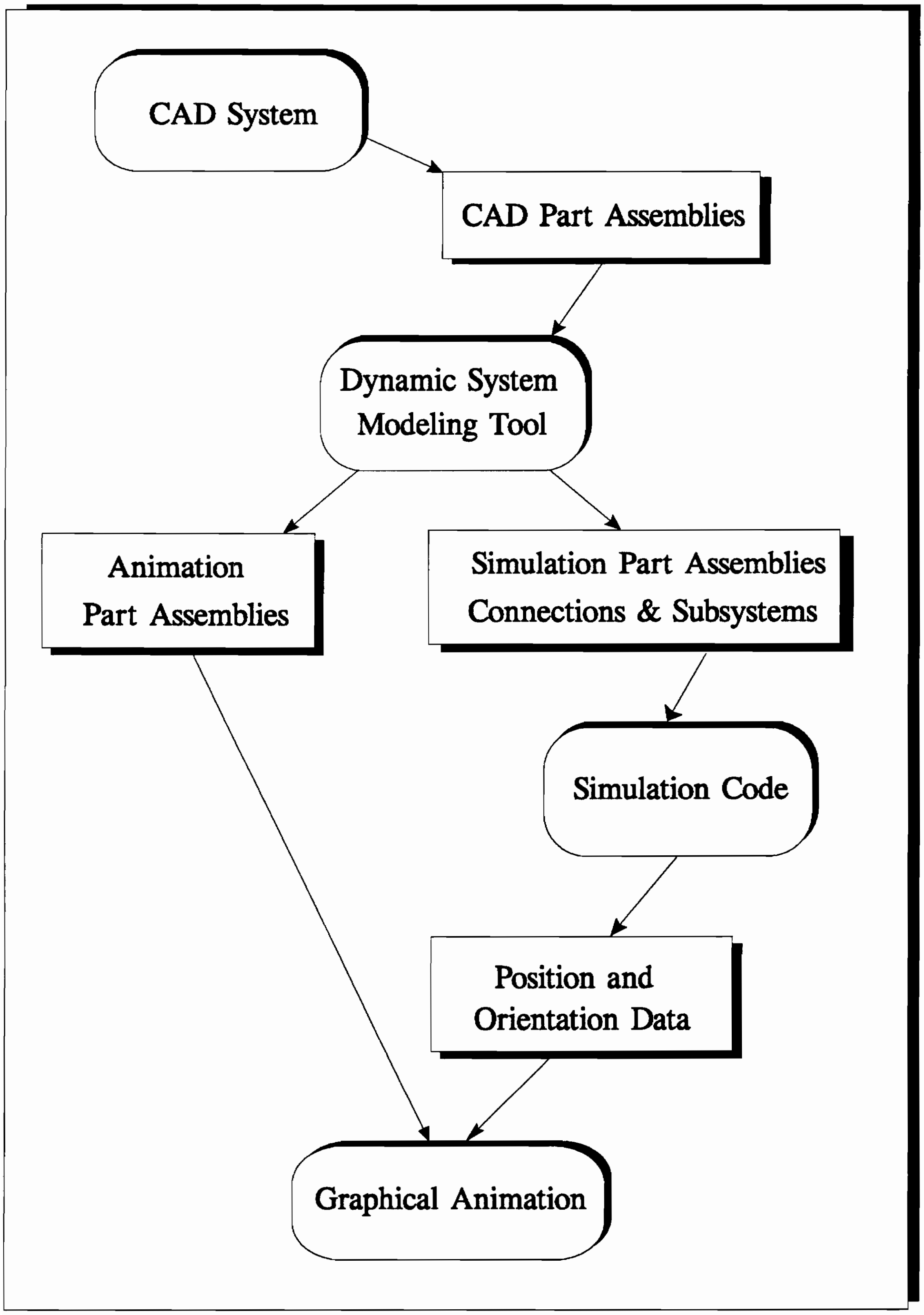

CAD System
CAD Part Assemblies
Dynamic System Modeling Tool
Animation Part Assemblies
Simulation Part Assemblies Connections & Subsystems
Simulation Code
Position and Orientation Data
Graphical Animation

Figure 5.1: Data Flow in a Simulation Environment (Wu et al. 1990)

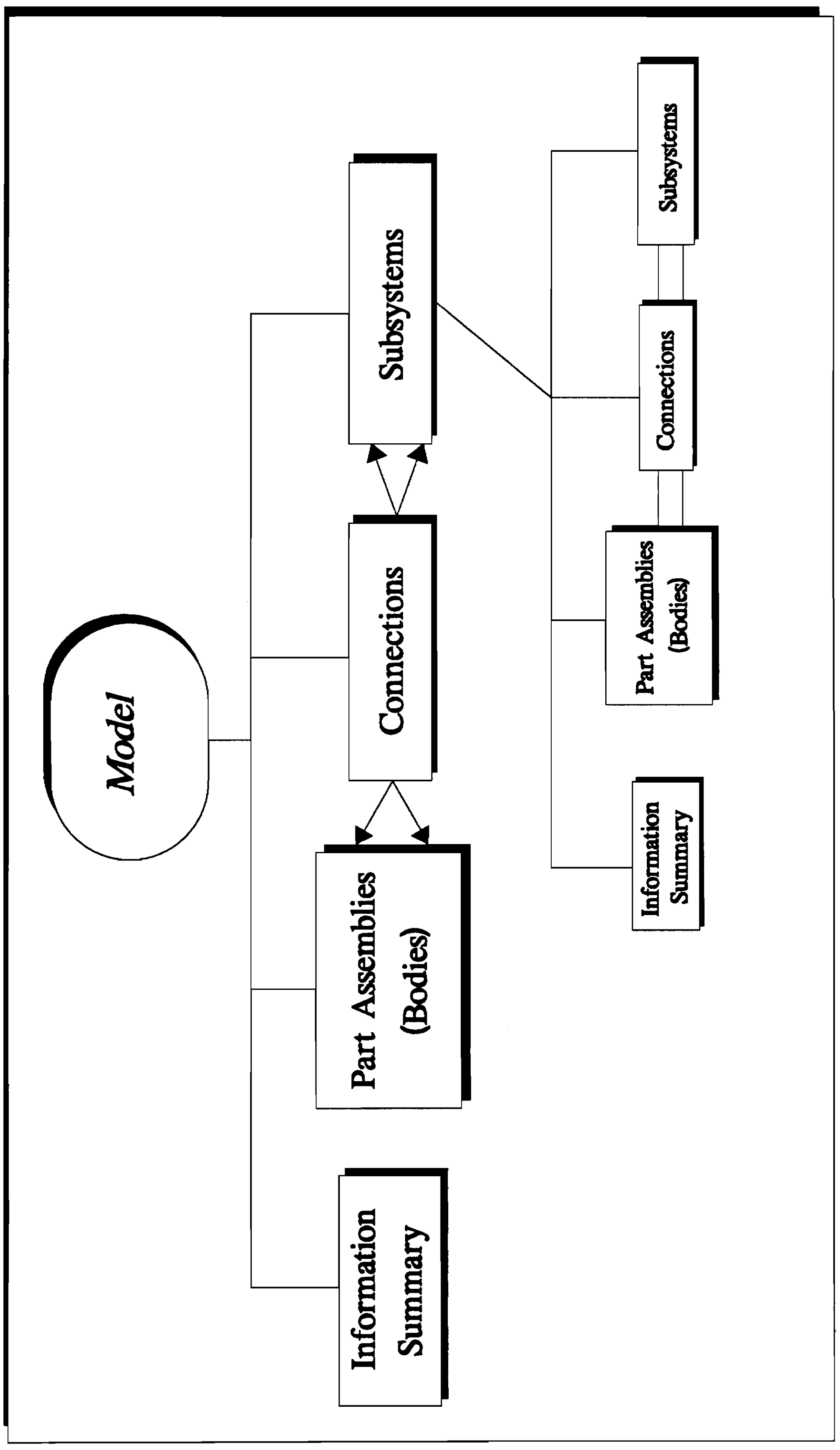


Figure 5.2: Hierarchical Structure of the Data Model

part assemblies, (2) subsystems, (3) connections, and (4) information summary. The following sections will describe these four components of the data model.

5.1.1.1 Part Assembly

A part assembly (or an assembly part) is an assembly of several member parts from the CAD system point of view. However, a part assembly is, in general, a body dynamic simulation point of view. A body is the smallest entity in the dynamic analysis. A body has its own kinetic property data and is connected to other bodies through joints. Member parts are rigidly connected together to form a body.

A part assembly has three application specific representations, as shown in Figure 5.3: (1) CAD part assembly, (2) simulation part assembly, and (3) animation part assembly. The attributes of each representation are explained as follows.

CAD Part Assembly

A CAD part assembly is an assembly of several CAD member parts. The CAD part assembly contains the composite property data and pointers to member parts, as shown in Figure 5.4. These composite properties can easily be calculated within WALKTHRU once the algorithm introduced in Chapter 3 is implemented into WALKTHRU.

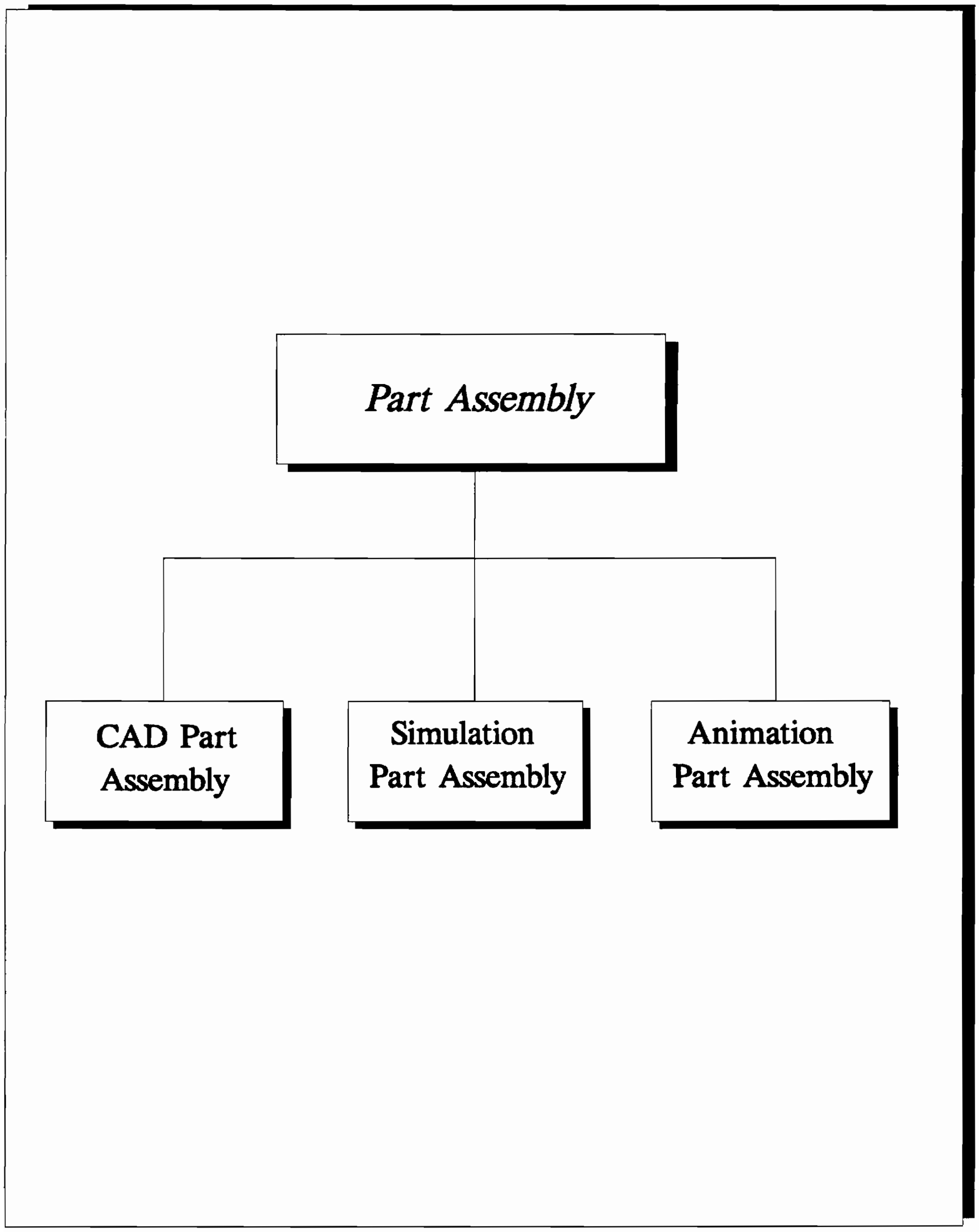


Figure 5.3: Components of a Part Assembly

CAD Part Assembly

Composite mass

Composite moments of inertia

Composite C. G. location

Pointers to CAD member part

Figure 5.4: Attributes of CAD Part Assembly

Each CAD member part consists of the attributes shown in Figure 5.5. Most attributes are self-explanatory. The attribute "attached part name" is the name of a member part that is assembled with the current member part. The name of the current member part is the attribute "part name".

An attachment reference frame is triad defined about the local reference frame of the current member part. The attribute "coordinate transformation" is an operand that can transfer the coordinates of an attached member part to the local reference frame of the current member part through an operation. This operation and operand can be a matrix multiplication and matrix, respectively. The type of connection should be a rigid connection for most CAD member parts. However, modifying the connection type is allowed when it is needed.

Geometric parameters define the geometry of a part. The form and meaning of these parameters depend on the geometric modeling system used. Schematic geometry layout is a rough outline of the geometry of the current member part for reducing graphic displaying time. Detailed geometry layout can show more detailed geometry. Both types of geometry layout use polygons to outline geometry of a member part.

Simulation Part Assembly

A CAD part assembly defines how a part assembly is constructed from a geometry point of view; whereas, a simulation part assembly contains additional information that are needed for dynamic simulation. The major additional attributes are connection reference frames and connectivity information. The entities used to define simulation part assembly are shown in Figure 5.6.

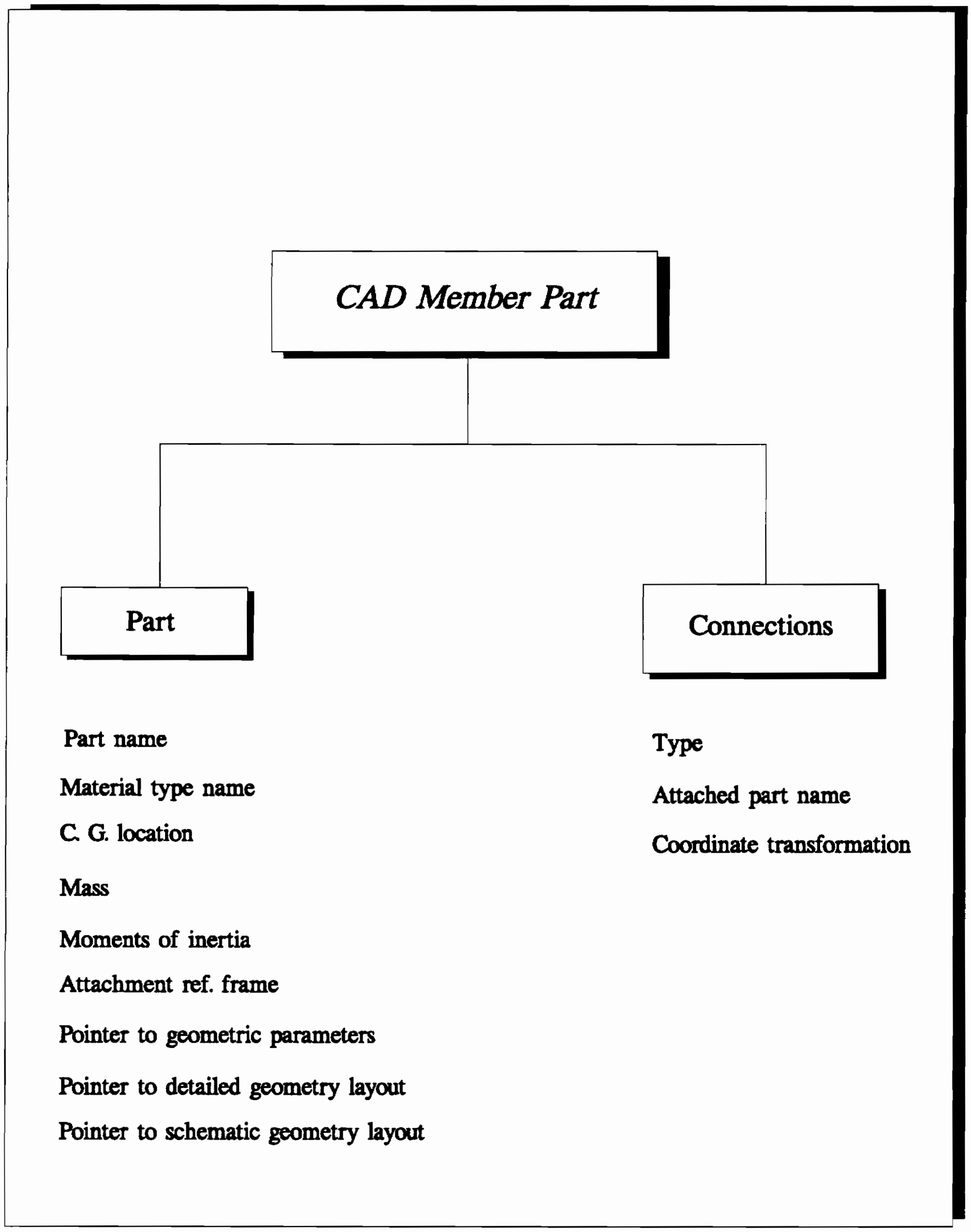


Figure 5.5: Attributes of CAD Member Part

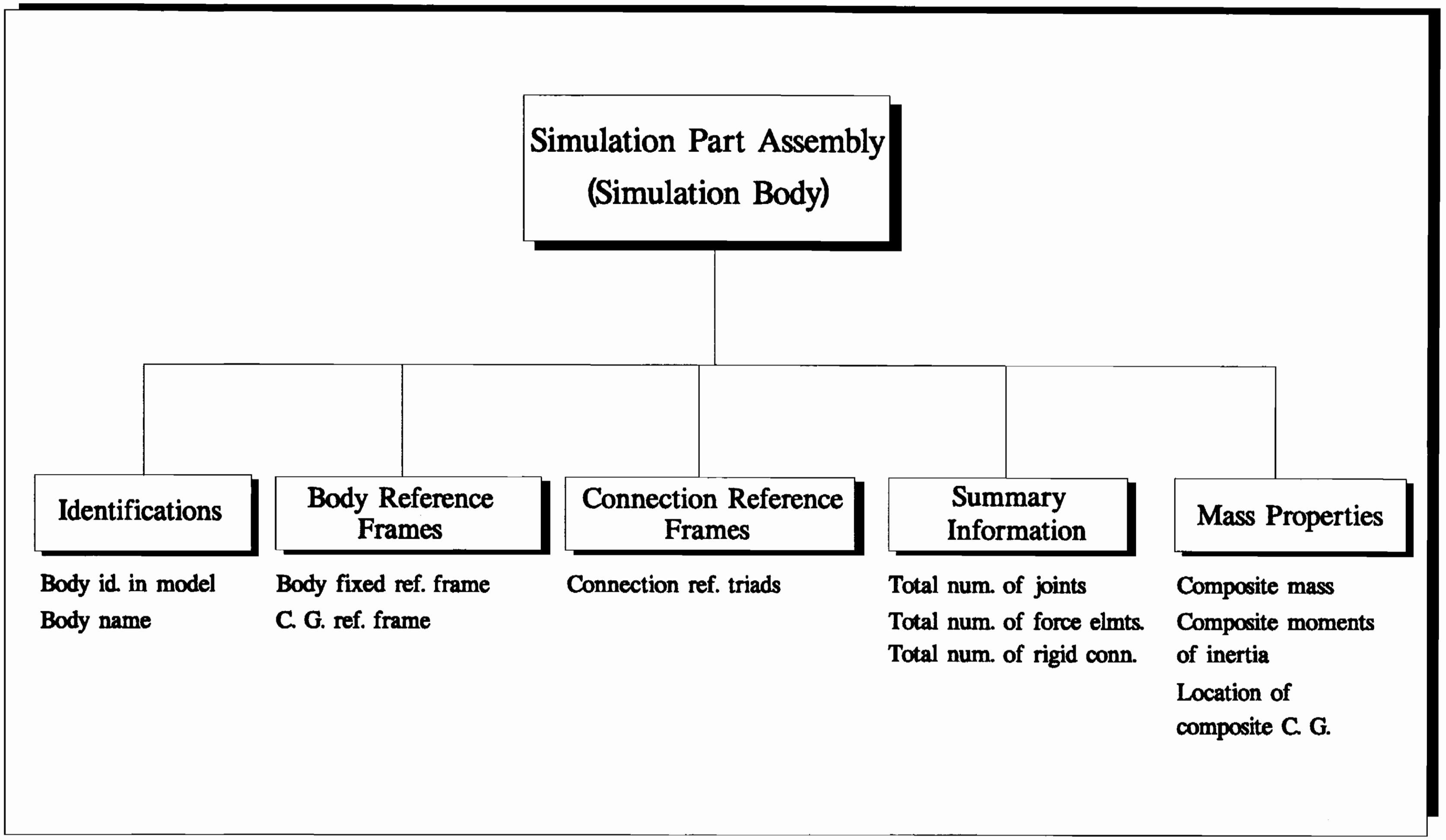


Figure 5.6: Attributes of Simulation Part Assembly

The "body name" is a user defined name which does not have to be unique. The attribute "body id. in the model" is a unique identifier of the body in the model.

The body fixed reference frame and center of gravity reference frame are triads. They have a composite data type frame. Attributes of a frame are shown in Figure 5.7. The frame location defines the origin of the reference frame. The frame orientation can be defined by two non-collinear vectors sharing the same origin that is defined by the attribute "frame location". The two vectors can be specified by three reference points (Haug 1988). The attribute "frame id." is the identification of the reference frame. The attribute "frame id. of rel. frame" is the identification of the reference frame relative to which the current reference frame is defined.

The connection reference frame, shown in Figure 5.6, is also a triad used to define the connection between a pair of bodies or part assemblies. The frame type should be of the three options shown in Fig 5.10 (p. 132), presented later in the thesis.

The composite attribute "mass property" keeps the values of composite mass property data. The composite mass property data can only be finalized at the model level (i.e., the highest level of the model). At the model level there is still a chance to attach several part assemblies to form a body for dynamic analysis.

The summary information contains the derived information, such as total numbers of joint, force elements, and rigid connections in a body.

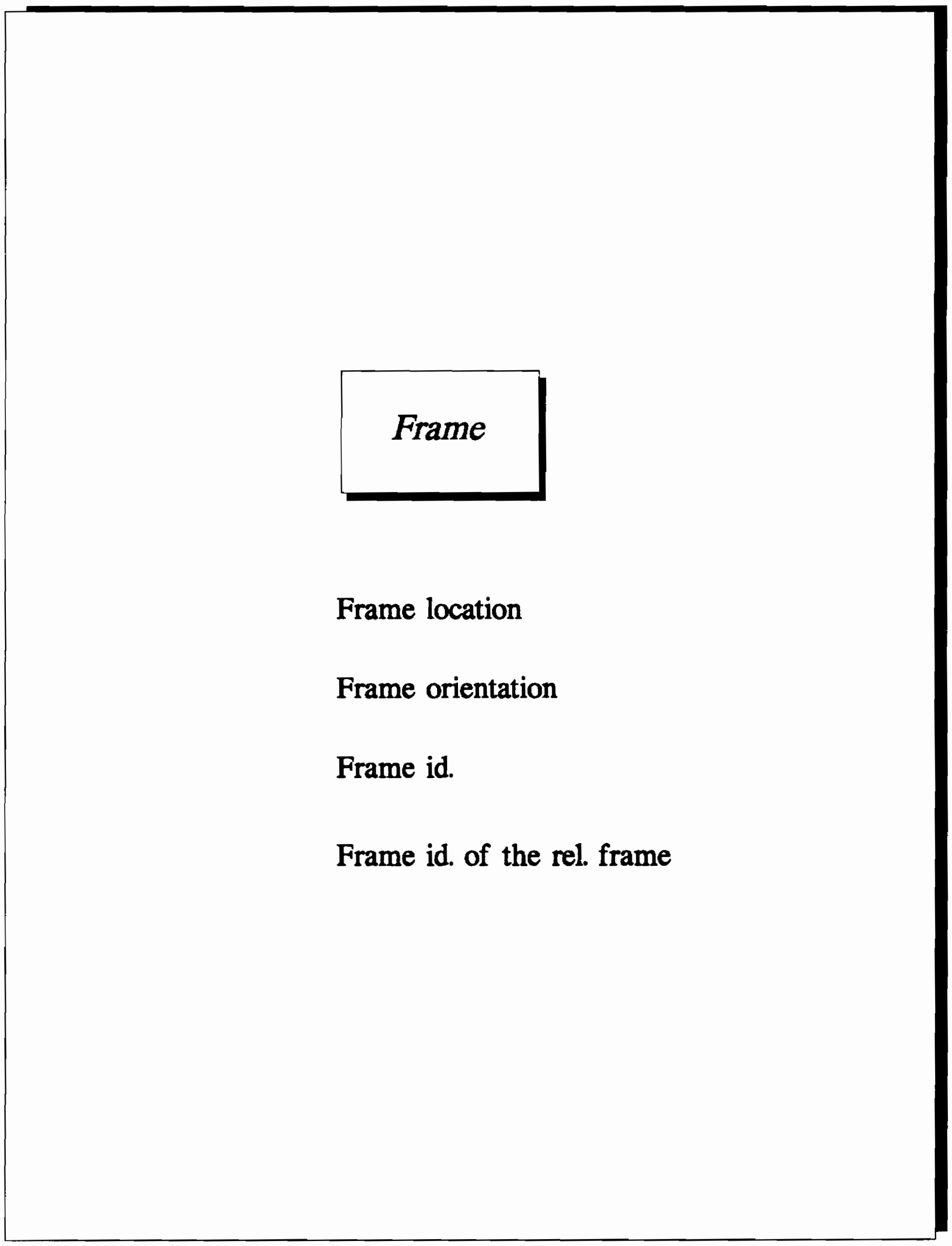


Figure 5.7: Attributes of a Reference Frame

<u>**Animation Part Assembly**</u>

Attributes of an animation part assembly define a general set of visualization parameters, as shown in Figure 5.8. The body color defines the color and intensity of a body. The attribute "visibility" defines in what form a body will be displayed on the screen. It can be wireframe, solid, transparent, etc. The transparency defines the degree of transparency of bodies, such that designers can see through them.

The body label is a useful aid for review the name of each body, if users forget the name of a specific body. Some freedom should be provided to manipulate the display of body labels. With properly selected values for specular and diffuse reflected parameters (Foley and van Dam 1985), the characteristic of the material surface and shading effects can be shown in graphical images. The ambient light parameters allow all visible bodies to have certain color intensity.

5.1.1.2 Connections

A connection is a functional device or relationship that produces kinematic constraints or forces to a pair of bodies or member parts. Thus, a connection represents a kinematic or force relationship between bodies and between parts. The connection reference has connectivity information and a flag, as shown in Figure 5.9.

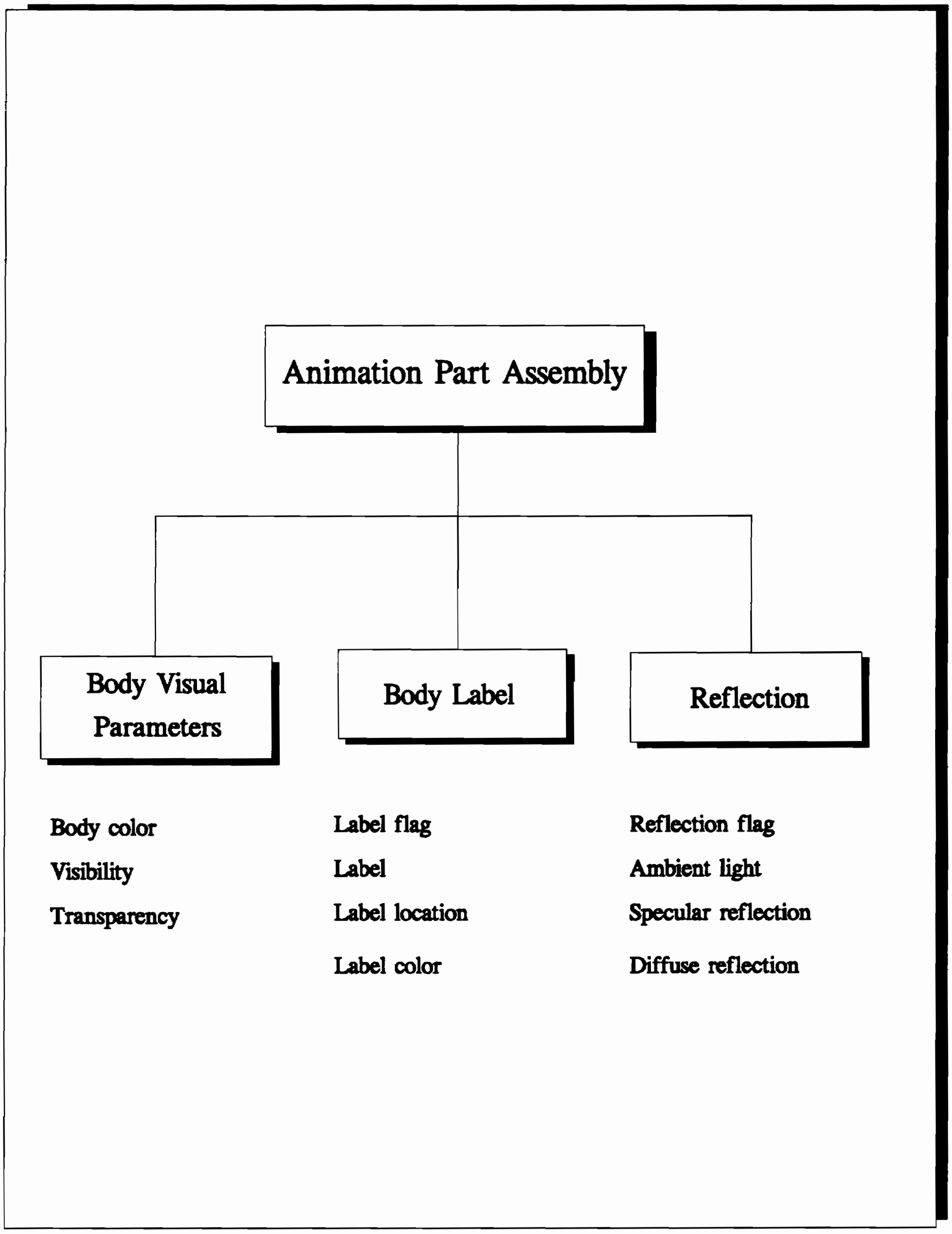


Figure 5.8: Attributes of Visual Parameters of Part Assembly

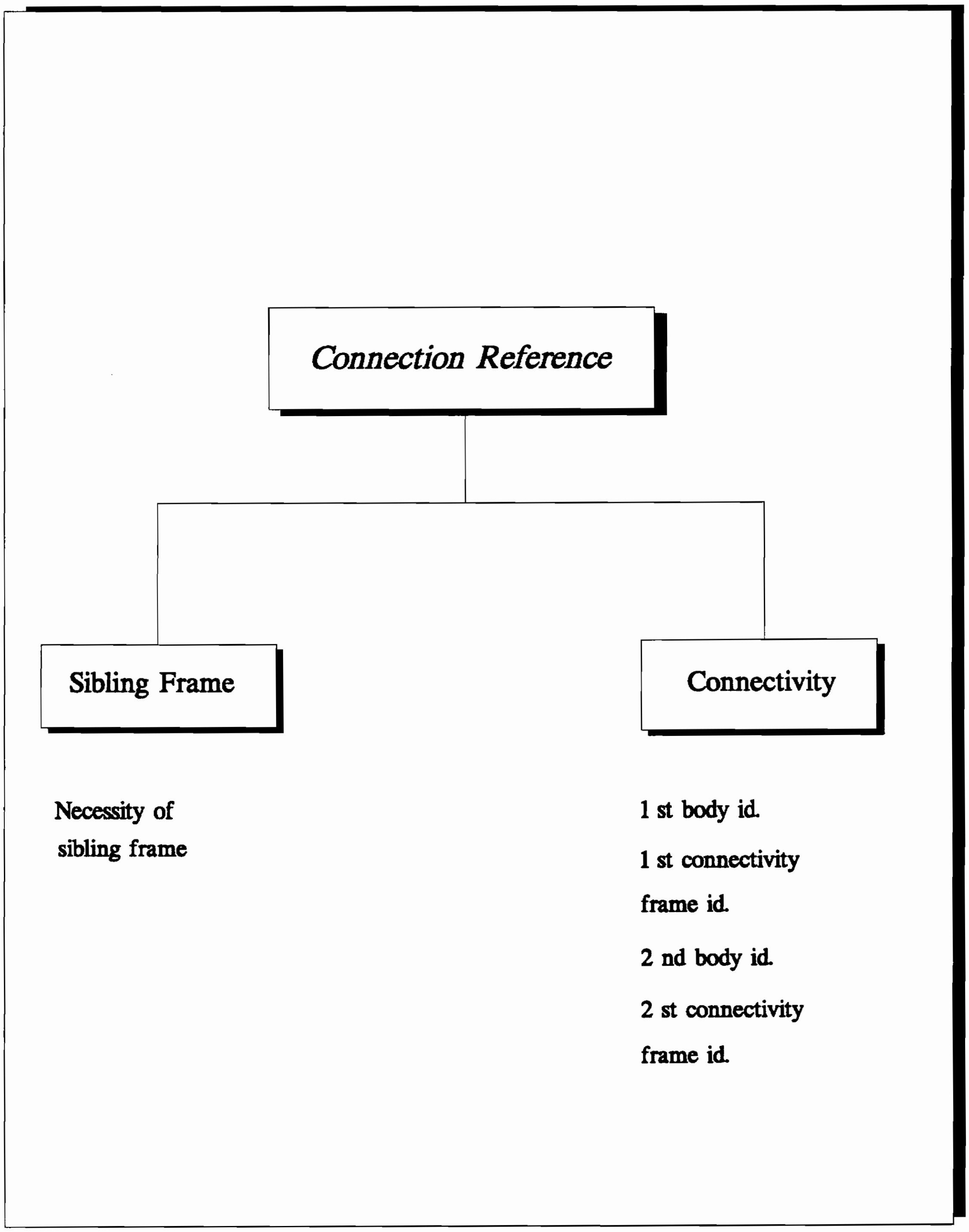


Figure 5.9: Attributes of General Connection Reference

The connectivity information includes body identifications and identifications of connectionreference frames. It should be noted that sometimes only one reference frame is needed in defining connections. If the situation that the locations of track supporting rollers are defined about the reference frame on a sprocket in a track suspension system. Once the location of the sprocket reference frame is defined about a hull, the locations of the rollers can be calculated. In this case there is no need to define the second reference frame for the connection that defines the connection between a hull and roller. The attribute "the necessity of sibling frame" should be negative for this case.

Three types of connections are considered in the conceptual development of the dynamic behavior modeler introduced by this thesis. These are: (1) rigid connection, (2) joint, and (3) force element, as shown in Figure 5.10.

Rigid Connection

A rigid connection is a device that rigidly fixes parts or subsets of part assemblies together. There is no relative motion between any pair of parts connected by a rigid connection. In general, entities connected by a rigid connection are member parts or incompletely defined part assemblies.

The rigid connection fixes two part assemblies into one composite part. The mass property data and the location of center of gravity need to be updated after the connection is done. This updating process will continue until all rigid connections have been considered. The final values of mass property attributes and the location of center of gravity will be those of a body in dynamic analysis.

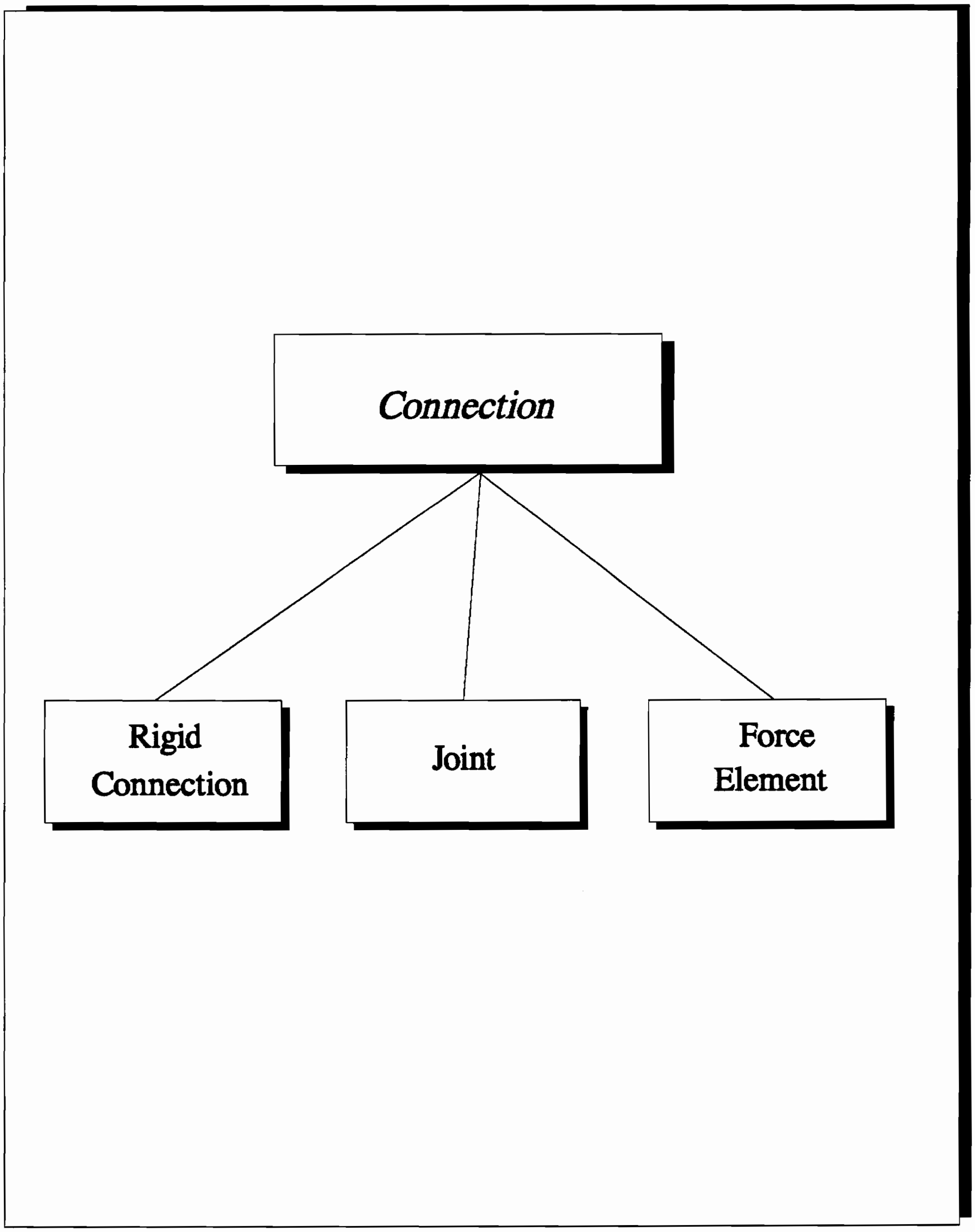


Figure 5.10: Connection Types

The attributes of a rigid connection are shown in Figure 5.11. Since the rigid connection is a special case of general connection (See Figure 5.10), the former will inherit the attributes of connection reference (See Figure 5.9). The coordinate transformation of the rigid connection is the same as that of the CAD member part (See Figure 5.5, p. 124). The attribute "connection id. in catalog" provides a path to get more detailed information, such as the type of connection (welded, or bolted, etc.).

Joint

A joint represents a kinematic relationship between a pair of bodies. A joint is very similar to a rigid connection with minor differences, as shown in Figure 5.12.

First, there is at least one relative degree of freedom between bodies connected by a joint. That means the coordinate transformation will not be constant. There are several types of joint which were shown in Figure 4.4 (p. 89). Each of them has different kinematic constraints. It is assumed that the attribute "joint id. in library" of a joint will provide the type information. Second, a joint can have one or several force elements attaching to it. Each joint may have associated springs and/or dampers which act to exert internal forces or torques within that joint.

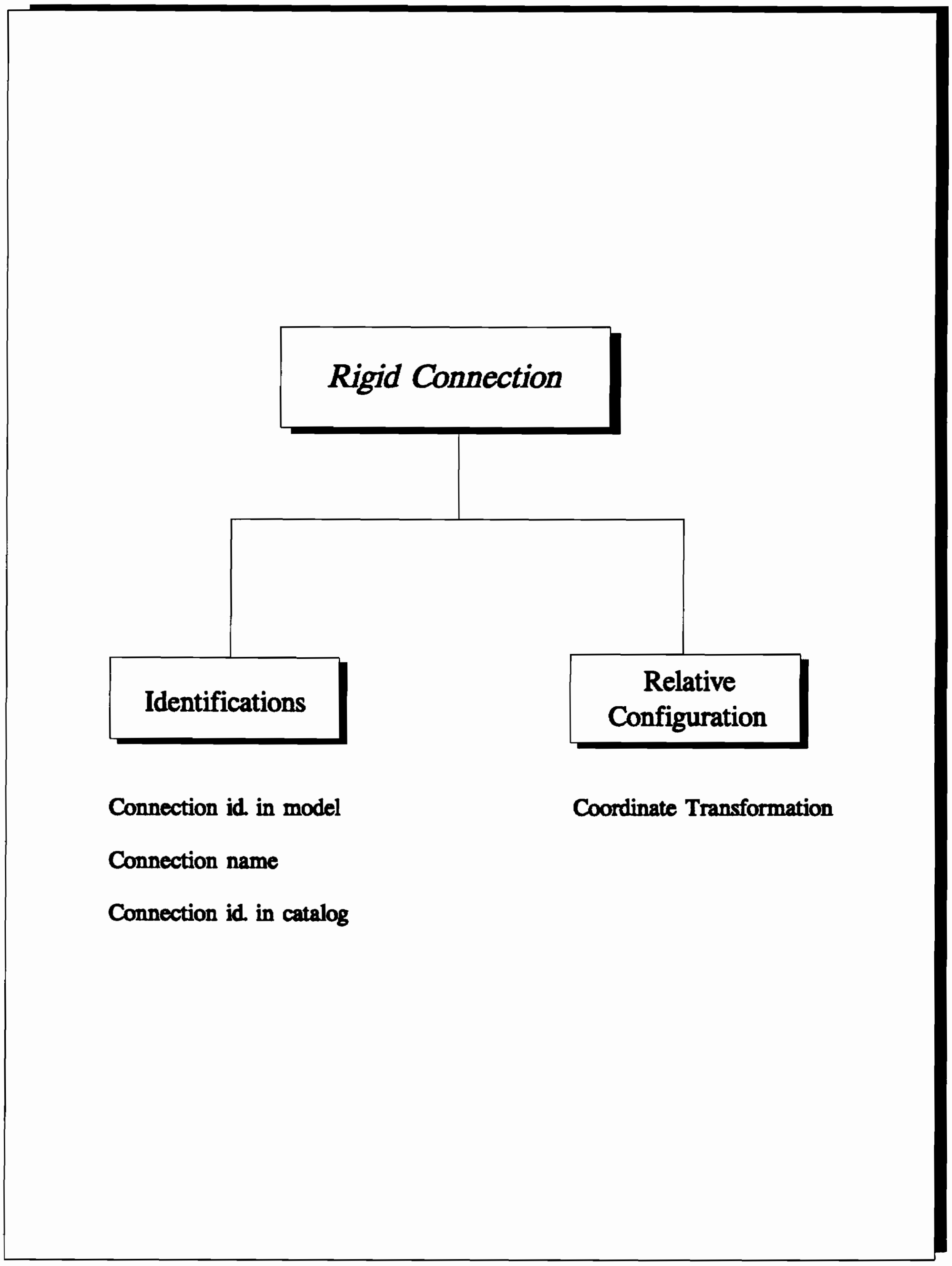


Figure 5.11: Attributes of Rigid Connection

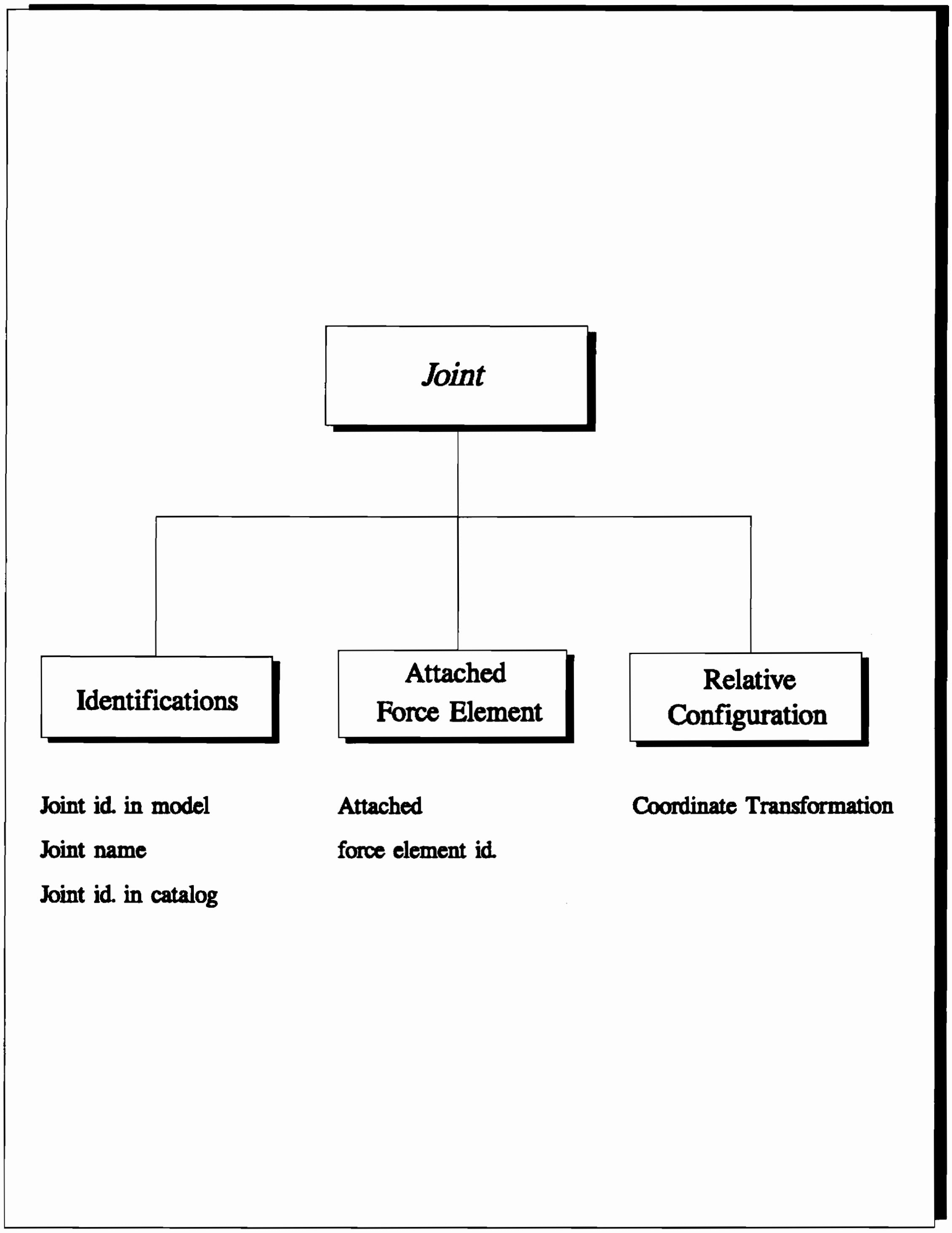


Figure 5.12: Attributes of a Joint

Force Element

A force element produces forces or torques to bodies or to a joint. When the force or torque is applied to a joint, the bodies connected by the joint will subject to that force or torque. This is why a force element is classified the same as a joint. Based on entities on which forces are applied upon, a force element can be classified as a joint force element, single body force element, or dual body force element, as shown in Figure 5.13.

A joint force element applies force (or torque) to a joint, such as a motor in a robot system. A dual body force element applies two forces (or torques) to two bodies. The forces are the same in magnitude but opposite in direction. For example, a hydraulic actuator between the dipper and boom of a backhoe system can be modeled as a dual body force element. A single body force element applies force only on a body. For example, the force applied to a rocket booster propulsion system can be modeled as a single body force element. Based on the physical device, force elements can be classified as a spring, damper, or actuator.

5.1.1.3 Subsystems

The subsystem is lists of part assemblies, connections, and subsystems, and summary information (See Figure 5.2, p. 119). The subsystem is a unit which provides a physical function for a large system (e.g., suspension system of a vehicle system). Conceptually, the subsystem is an instance of a model. A subsystem may have its own subsystem. Ultimately, a subsystem can be a model. With the subsystem structure available in the data model, recursive model generation is feasible. It also simplifies the modeling procedure significantly.

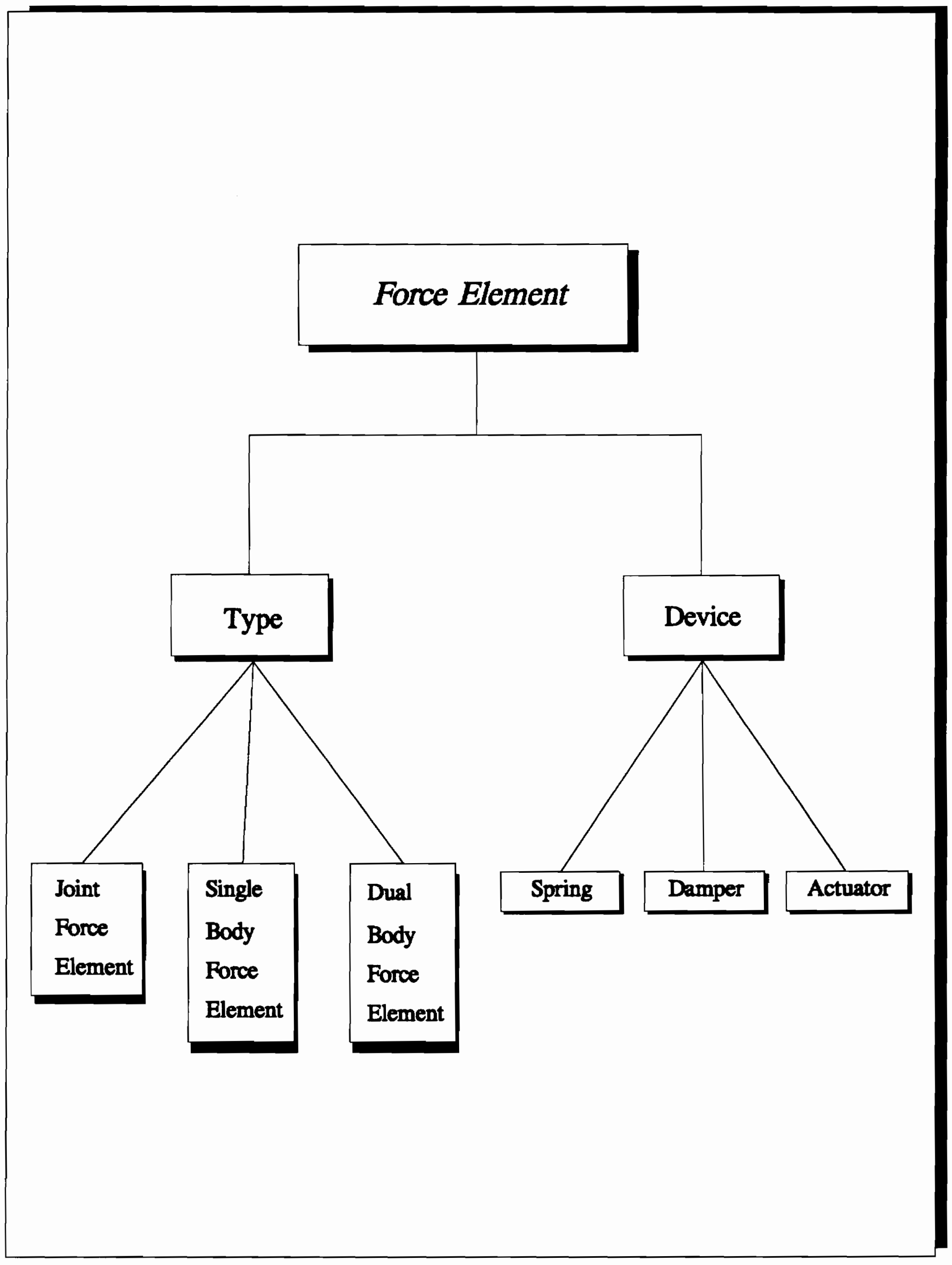


Figure 5.13: Options in Force Elements

5.1.1.4 Information Summary

As a component of the data model shown in Figure 5.2 (p. 119), a summary of model information is useful in describing the model, especially for inputting model data to analysis code. Such a summary may include total numbers of bodies, joints, force element, degrees of freedom, etc.

Section 5.1.1 has provided a look at the attributes of assembling information and visual parameters involved in a data model for rigid body dynamic system modeling, simulation, and graphical animation.

The following section will discuss the dynamic system modeling component of the data model which is to integrate CAD/CAE systems with WALKTHRU. The dynamic behavior modeler presented in Chapter 4 contains the required attributes and generates the required simulation data to be considered as a "dynamic system modeling tool" in the data model. The following section will look at the position of the dynamic behavior modeler in the data model and discuss the significance of the dynamic behavior modeler for the data model.

5.1.2 Dynamic System Modeling Tool

As shown in Figure 5.1 (p. 118), dynamic system modeling tool is utilized along with a CAD system, to generate the data model of a mechanism. Also as mentioned before, the data model is then used to extract the corresponding model for simulation. Geometric and assembling information derived from the data model and position and orientation data obtained from simulation results are used for animating the dynamic behavior of the system.

In presenting their data model, Wu et al. (Wu et al. 1990) lack the development of the dynamic system modeling tool and the strategies to obtain position and orientation data. However, the dynamic behavior modeler presented in Chapter 4 is capable of serving as a dynamic system modeling tool and providing position and orientation data for a generic data model.

The significance of the dynamic behavior modeler can be seen in Figure 5.14 which illustrates the contents of mechanical system design. Mechanical system design is a process to iteratively define, evaluate, and modify the model of a product. In the design process, a model may be used in several simulations and animations to evaluate the performance of the design. Hence, it is not enough to have a model generated only with attributes based on physical and geometrical data (assembling information attributes as described in Section 5.1.1). It is necessary to generate data based on dynamic simulations to create a realistic model. The dynamic behavior modeler presented in this thesis is believed to be capable of serving in a generic data model for dynamic system modeling, and dynamic simulation for computer animation.

The required input for the dynamic behavior modeler was shown in Figure 4.3 (p. 86). The "physical model" component of the required input matches with the attributes of part assemblies (CAD, simulation, and animation) and connections which were discussed in Section 5.1.1. However, in order to generate simulation data and update the values of the

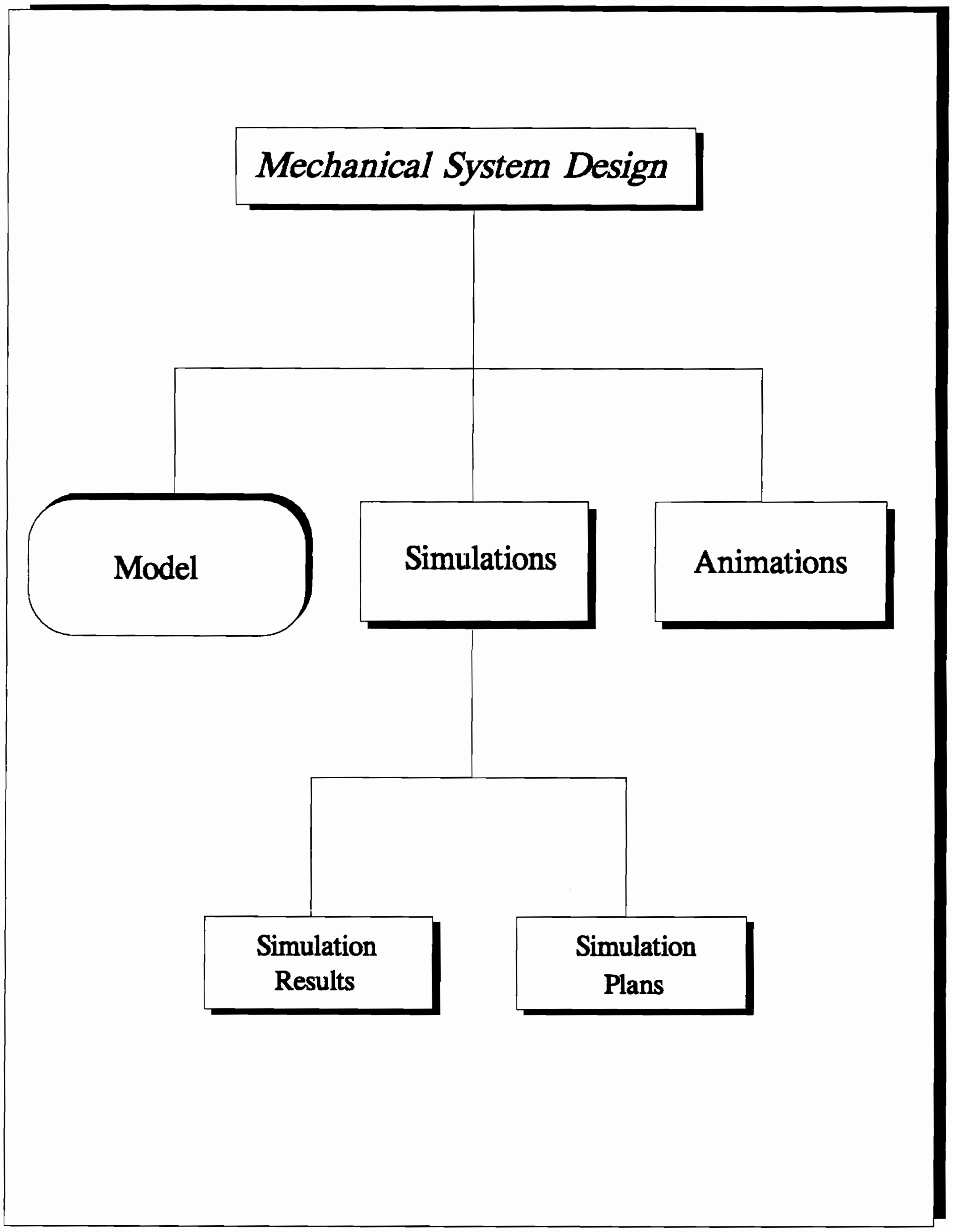


Figure 5.14: Contents of Mechanical System Design

physical properties under dynamic behavior, there is a need to incorporate the "behavior" component of the required input into the data model.

There is also a need to perform the "dynamic analysis" module (See Figure 4.3, p. 86) of the dynamic behavior modeler to determine the orientation and position data. As shown in Figure 5.1 (p. 118) orientation and position data are essential to achieve a realistic graphical animation. The dynamic analysis module of the dynamic behavior modeler is capable of serving this purpose.

The attributes of the components of the dynamic behavior modeler and the strategies involved in them were discussed in detail in the previous chapter.

5.2 Summary and Conclusion

This chapter has presented a data model for integrating CAD/CAE systems and WALKTHRU. The data model has been explained in a conceptual level. Such a data model is envisioned for rigid body dynamic system modeling, simulation, and graphical animation. The data model is expected to contribute to the productivity improvement in the design and planning phases of engineering by simplifying the modeling procedure.

WALKTHRU is an appropriate environment to be integrated with CAD/CAE systems. However, there is a need to create new data structures to define and store the attributes of the data model. In addition, it is required to modify the binary files of WALKTHRU to animate the dynamic behavior of the objects realistically.

The data model is based on the conceptual aspects introduced by Wu et al. (Wu et al. 1990). However, a solution for the dynamic system modeling issue which is lacked by Wu et al. has also been introduced.

This solution is through a dynamic behavior modeler. The main objective of this thesis is to conceptually develop a dynamic behavior modeler to be included into a multi-tasking motion planning system for material handling operations in construction. The dynamic behavior modeler presented in Chapter 4 serves this objective by providing an insight into real life performance of the mechanisms involved in material handling. Also, the dynamic behavior component, capable of dynamic simulation for computer animation is believed to be of significance in a data model which serves as a basis for integrating CAD/CAE systems and WALKTHRU. Such a data model with the incorporation of the dynamic behavior modeler will undoubtedly provide WALKTHRU with design and analysis facilities besides realistic simulation and animation capabilities.

Provided with a technology (a dynamic behavior modeler incorporated in a data model) which ensures a realistic visualization and a reliable data generation for design evaluation through dynamic simulation for computer animation, WALKTHRU can significantly contribute to the modeling process in the following areas:

1- Debugging and verification
2- Validation
3- Analysis
4- Communication and presentation

These four modeling phases will be examined below.

Debugging and Verification

From the modeler's perspective, animation is a powerful tool during development of a model. Since an animation is simply a graphically depicted sequence of events occurring in the simulation (trace), it provides an informative, user-friendly tool for debugging and verifying models. Animation provides the capability to follow simultaneously several objects as they travel through the system. Animation is also useful for understanding object interaction or events which concurrently occur. Complicated interactions among many objects in a model are often difficult to grasp when working only with a trace of model statements.

Initially, WALKTHRU can be used to assist with isolation and removal of errors in the model. Later, it can be used to examine the underlying control logic of the model. As Hollocks (Hollocks 1984) states, "Graphics provides a further dimension to the verification of simulation models." However, the modeler's success in using animation through WALKTHRU for debugging and verification is at best only a partial verification of the system. Unless the model is rigorously animated, much of the information which might be provided by a trace is not displayed. Thus, a correctly functioning animation does not imply a completely debugged model, much less a verified model. Moreover, WALKTHRU's animation capability should be viewed as one of many tools in the verification process. As stated by Smith and Platt (Smith and Platt 1987), "Animation does not eliminate the need for manual checking of calculations or for statistical verification methods, but it does serve as an important productivity tool for augmenting these methods."

Validation

The link between animation and model validation, while only partial, is still very important. Model validation is defined as "substantiation that a computerized model within its domain of applicability possesses a satisfactory range of accuracy consistent with the intended application of the model" (Schlesinger et al. 1979). Ensuring that a model truly represents the real system (actual or proposed) is a complex task including validation of model concept, data and operation. This should not be confused with model verification, which is the process of ensuring that the computer code is a correct implementation of the conceptual model, as shown in Figure 5.15.

Since in many cases, the simulation modeler is not the system expert, WALKTHRU's animation capability can provide a vital link between the modeler and expert, as shown in Figure 5.16. This contributes to the conceptual model (mathematical/verbal/logical) validation process.

Such validation is often conducted by the system expert, who inspects and evaluates the model to determine if it is really reasonable and correct for its intended purpose. In many cases, the system expert is unfamiliar with the simulation environment, ruling out a direct inspection of the simulation model (written in computer code). Alternative communication may take the form of verbal and written descriptions, static graphic representations (i.e., flow charts), or relational descriptions (mathematical and logical). WALKTHRU can play an important role in this process. Since an expert has a thorough understanding of the system, only a moderate amount of graphical detail is necessary for the expert to fully recognize the system and understand many of the modeling concept. Such graphic

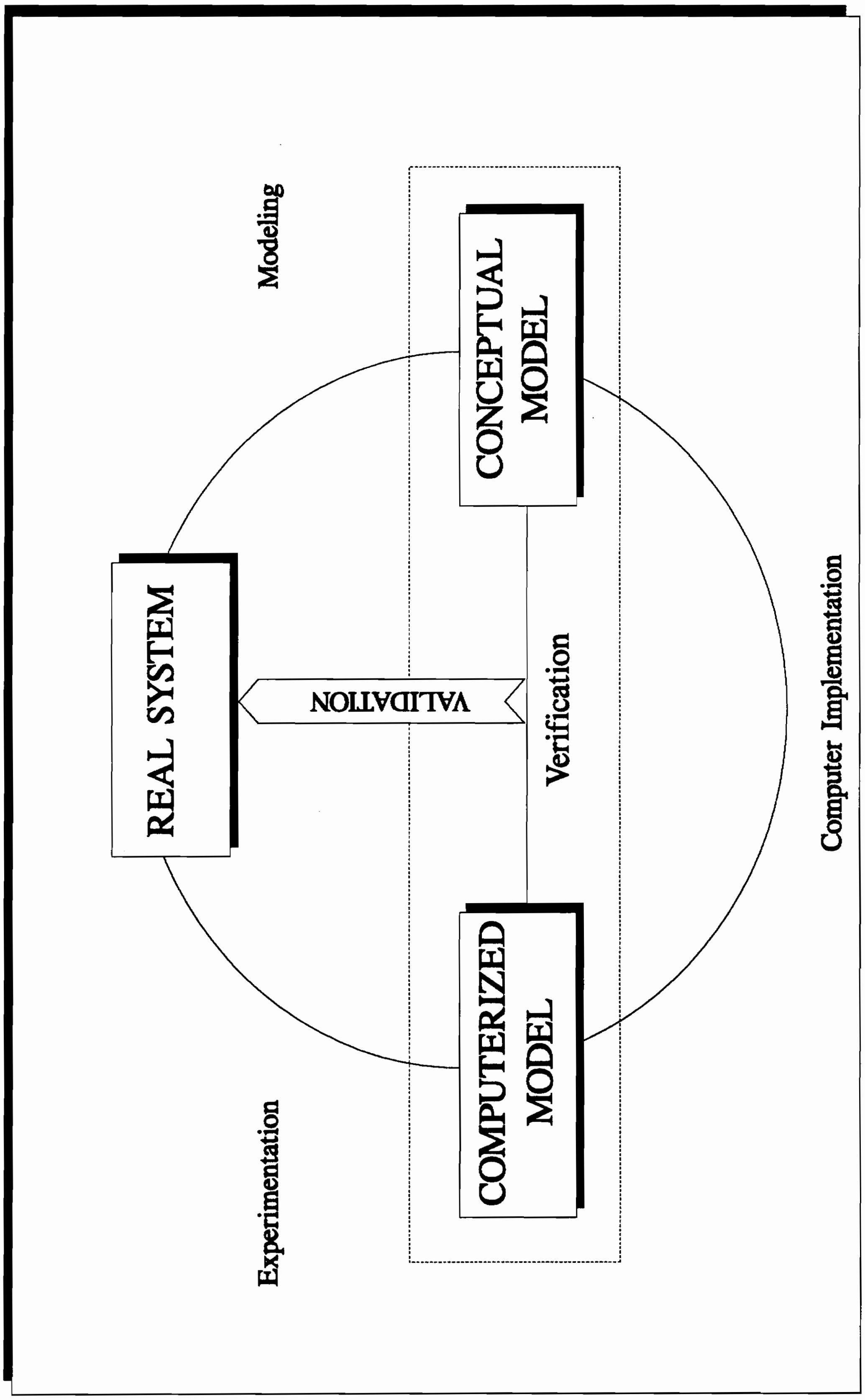


Figure 5.15: Modeling Process

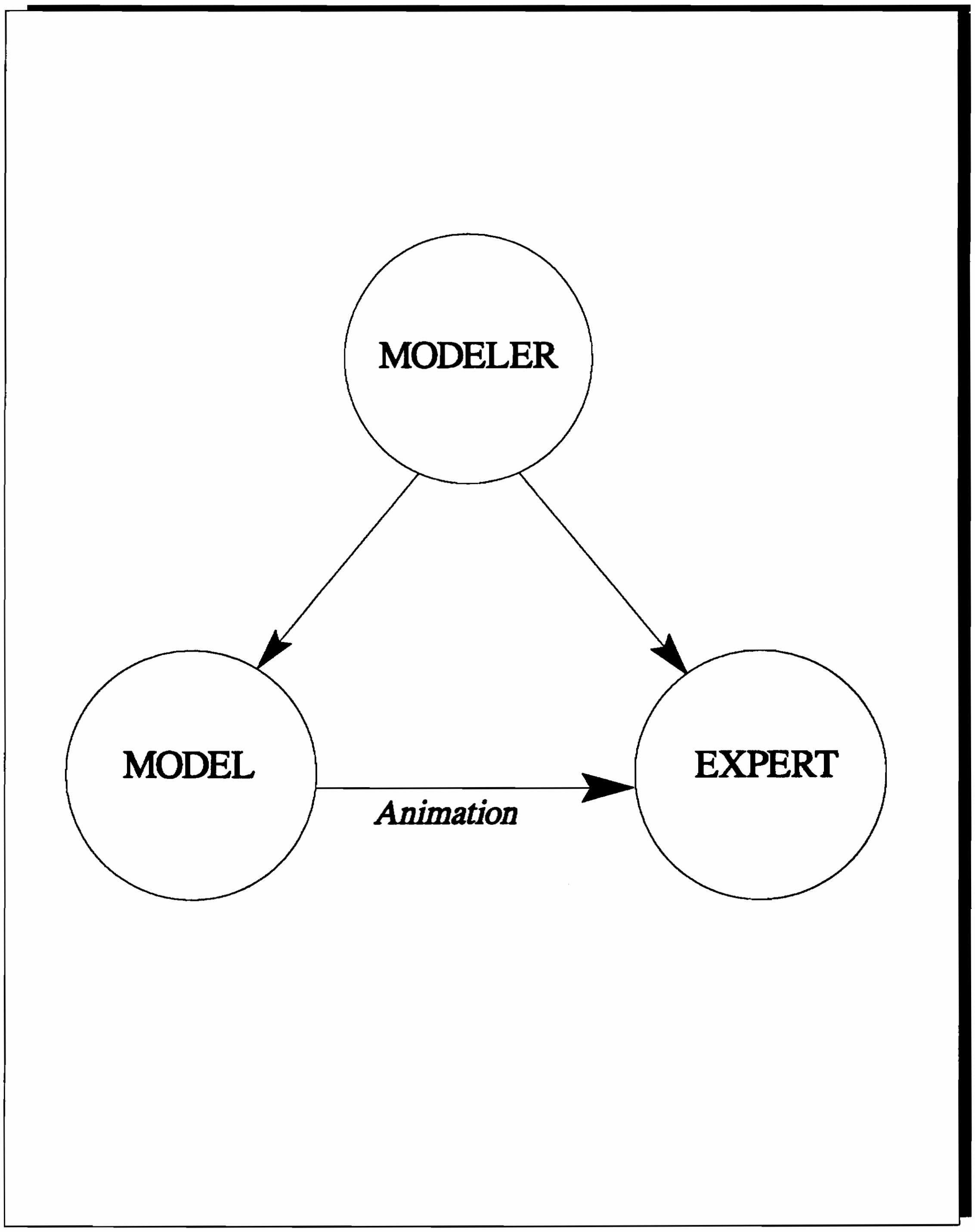


Figure 5.16: Animation: Link Between Model and Expert

communication is very efficient and provides a basis for constructive criticism and discussion of the model.

Analysis

As an analysis tool, animation can be applied in a variety of situations. The ability of the analyst to observe the interactions of many simultaneous and interrelated events provides information unavailable in aggregate statistical performance measures. In some cases, the values of such performance measures indicate problems, but can not identify the source.

For example, WALKTHRU with its enhanced capabilities can be used in the analysis of a multi-tasking material handling process. The process can be simulated dynamically taking the effects of external and internal forces on the mechanisms into consideration; and conflicts, if any, can be detected prior to the actual operations. Through the capabilities of the dynamic behavior modeler, new constraints and/or new limitations on the motion and the loads can be determined. Such an analysis capability can be of significant help in collision avoidance.

Communication and Presentation

Unquestionably, one of the greatest contributions of animation to the modeling process is presentation. Through dynamic movement and color, animation portrays the complexity of system interaction never fully described by static graphics and written communication.

Since the overall objective of any modeling effort is to provide information to the decision maker, it is critical that the information be credible for it to be considered. While the decision maker does not validate the model, he/she must decide to accept or reject the modeler's claims concerning information derived from the model. This acceptance is often based on the modeler's presentation. Obviously, effective communication is directly linked to credibility. Animation provides effective communication necessary to sell the proposed solution.

WALKTHRU already possesses a superb technology for representation purposes in its current version. However, the current representation information's credibility will certainly improve due to a more realistic visualization capability provided through the dynamic behavior modeler.

The dynamic behavior modeler presented in Chapter 4 performs dynamic simulation for computer animation. One of the major contributions (discussed in Section 4.2.6) of such a modeler is a realistic visualization capability. The generic data modeler for WALKTHRU presented in this chapter has the dynamic behavior modeler as its dynamic system modeling tool. Such a data model will serve a basis for integrating CAD/CAE systems with WALKTHRU. The data model which helps simplify the modeling process is intended for dynamic system modeling, dynamic simulation, and graphical animation.

The incorporation of the dynamic behavior modeler and the generic data model will undoubtedly extend the current capabilities of WALKTHRU. An enhanced WALKTHRU will be of significant help in the planning, control, modeling and design evaluation phases of engineering projects. Such a tool will contribute to the improvements in productivity of engineers, and hence to the improvements in the overall performance of the projects.

Next is the concluding chapter. The previous chapters will be briefly reviewed. A conclusion of the work will be presented. Also, recommendations, and future advancements will be addressed.

CHAPTER 6

CONCLUSION

This chapter reviews the previous chapters, points out the recommended uses and significance of the dynamic behavior modeler. Also, the potential future extensions are stated. The final section of this chapter provides a conclusion.

6.1 Summary

This thesis has presented the theoretical aspects of a dynamic behavior modeler to perform dynamic simulation for computer animation. In traditional animation, objects in a scene are looked upon as geometric shapes devoid of dynamical properties. The result is that the operator is forced to use his/her intuition about the physical world in planning the motion of objects in the scene. However, such techniques have generally proven unsatisfactory, since real motions tend to be complex. In order to achieve a satisfactory degree of realism and a tool for predicting real behavior under dynamic loading, the motion of objects must be simulated by the physical principles of dynamics governing the motion.

The dynamic behavior modeler introduced in this thesis has the capability of realistically modeling the dynamics of 3-D motions of rigid bodies. In addition to performing dynamic simulation, the system contains three means for achieving control. These three means are:

(1) The imposition of 'kinematic constraints' permits traditional animation systems to be embedded within a dynamic analysis.

(2) The ability to define 'behavior functions' allows the objects to react to its surroundings.

(3) A process of 'inverse dynamics' provides a means of determining the forces required to perform a specified motion.

The above mechanisms provide control without disrupting the dynamic integrity of the resulting motion. The theoretical aspects of the dynamic behavior modeler were discussed in detail in Chapter 4.

In addition, Chapter 4 presented a sample case which has been coded in GL programming language for animation. The sample case involves a mobile crane in a "pick and place" task. The animation created is not based on dynamic simulation. The traditional animation methods were employed for the sample case; however, the animation provides an insight to the realistic visualization that could be achieved through the dynamic behavior modeler presented in this thesis. Some approximations and assumptions have been made in the development of the analytical model without disrupting the realism of the dynamics of the sample case. These approximations and assumptions have been introduced to improve the efficiency of the animation.

The major motivation behind the dynamic behavior modeler has been identified as the need for multi-tasking motion planning for material handling in construction. The modeler is envisioned as an essential component of a multi-tasking motion planning (MTMP) system. The MTMP system will provide a geometric solution to multi-tasking motion planning for material handling in construction. This will lead to an effective plan and control of conflicting multiple material handling operations. Also, MTMP capabilities will play a major role for the automation of material handling process in construction. The three major components of MTMP are: (1) dynamic behavior modeler, (2) dynamic motion planner, and (3) simulation and control for automation/robotics. The MTMP system was described in detail in Chapter 2.

The platform to implement the dynamic behavior modeler and the MTMP system is envisioned to be WALKTHRU, a 3-D simulation and animation software. The development of the dynamic behavior modeler heavily relies on incorporating integral properties (mass properties) of solids into WALKTHRU. In order to plan or control static or dynamic behavior of objects in simulation and animation applications, it is necessary to evaluate integral properties of solids (e.g., volume, center of gravity, mass moments of inertia, etc.). The incorporation of these properties enables the use of the physical quantities (e.g., inertial forces, external forces, torques, etc.) in addition to geometry to better model and control the environment. The incorporation of the integral properties of solids into WALKTHRU was discussed in Chapter 3.

Many CAD/CAE systems which provide engineers with geometric modeling, part assembly, and simulation capabilities have been developed to analyze performance of design from different aspects. Such systems are of significant help for engineers in evaluating the overall performance of their design. Simulation and animation packages are among these systems. The dynamic behavior modeler introduced in this thesis can be incorporated into a generic data model which will serve as a basis for integration of CAD/CAE systems with WALKTHRU. Such a data model can provide the technology for rigid body dynamic system modeling, simulation, and graphical animation. The attributes of a data model for WALKTHRU were presented in Chapter 5.

The following section points out the recommended uses and significance of the dynamic behavior modeler.

6.2 Recommended Uses and Significance

The dynamic behavior modeler presented in this thesis is intended to be used to dynamically simulate linked 3-D rigid body systems for computer animation. As stated before, the dynamic behavior modeler is to be included in a multi-tasking motion planning system for material handling in construction at a future date. Hence, the modeler will essentially be utilized to model and simulate the material handling operations involving cranes and robots.

The major contribution of the dynamic behavior modeler will be the capability to ensure a satisfactory degree of realism in visualization of the material handling operations. This will be achieved by a realistic prediction of the dynamic behavior of mechanisms involved in these operations. So far, there has not been a system which considers the dynamic behavior of mechanisms during motion planning. The dynamic behavior modeler, once included into MTMP, will provide a novel approach to realistically model motion planning process.

Material handling operations in construction is one of the areas which will significantly benefit from the dynamic behavior modeler. The dynamic behavior modeler will be used throughout the planning phase of the construction projects by engineers. The modeler will allow engineers to animate the material handling operations based on dynamic simulation. The engineers will be able to model critical rigging operations realistically. The realistic and reliable visualization provided through the modeler will enable engineers to better plan, model, and control material handling in construction. This will further lead to significant improvements in constructability and performance of the construction projects. Accidents and rework will be reduced, while safety and productivity will be improved, and high quality and timeliness will be ensured throughout the operations.

In addition, the dynamic behavior modeler can be of significance for the development of a generic data model which serves as a basis for integrating CAD/CAE and visualization systems. The dynamic behavior modeler can be utilized to generate the data required for dynamic system modeling, simulation and graphical animation. Once incorporated in such a data model, the modeler will not only provide a realistic visualization but will also ensure a reliable design evaluation.

A generic data model with the dynamic behavior modeler will provide the technology required to extend WALKTHRU from a 3-D simulation and animation package to a system with design and analysis capabilities. WALKTHRU with such capabilities can be used by engineers in modeling process of mechanisms and can contribute in debugging and verification, validation, analysis, and communication and presentation areas throughout the modeling process.

The following section will provide a look at the potential future extensions to the dynamic behavior modeler.

6.3 Future Extensions

Full implementation and testing of the conceptual dynamic behavior modeler presented in this thesis need to be done in the future. In addition, there are several features which can be included within the dynamic behavior modeler. However, first a brief look at the work that should be done to implement the dynamic behavior modeler into WALKTHRU will be presented.

The dynamic behavior modeler first needs to be coded in C programming language. This requires that behaviors be compiled and linked with the simulation code. C is a "so-called higher level language, yet it provides capabilities that enable the user to get in close with the hardware and deal with the computer on a much lower level" (Kochan 1988). This is because, while the C language is a general purpose structured programming language, it was designed with systems programming applications in mind, and as such, provides the user with an enormous amount of power and flexibility. Hence, a higher level language like C is a naturel choice for the implementation of the modeler and to enhance the process of developing behavior functions.

Also, within WALKTHRU there is a need to create new data structures to store physical properties, connectivity relationships between objects, kinematic constraints, joint definitions, local coordinate frames, etc. The binary data structure of WALKTHRU has to be modified to attain an ability to update and store new coordinates between keyframes during animation. This will enable the true presentation of deflections and deformations on the objects within the modeled environment. Ultimately, the extensions and modifications for WALKTHRU are required for dynamic simulation for computer animation.

Additional desirable features include: the implementation of closed kinematic chains, behaviors that learn, a flexible user interface for defining linkages and behaviors, and the ability for objects to interact in parallel through message passing, i.e., message passed from behavior to behavior.

Another extension may be a collision analysis capability. Through collision analysis, the interaction among objects can be simulated realistically in a completely general way. This includes continuous contact and complex contact geometry, allowing the solution of general constraint problems including 'non-holonomic' constraints. Such a capability has been introduced by Hahn (Hahn 1990). Hahn states that "collision analysis makes it possible to solve the constraint problems using only the absolute minimum quantities needed to describe motion, the first derivatives of position and orientation (velocity and angular velocity)".

Finally, the dynamic behavior modeler can be extended with a capability to analyze stresses and strains due to dynamic loading. This can be achieved through incorporation of a finite element analysis capability. Stresses and strains can be modeled for each component of the material handling process. This will ensure proper and safe planning of a multi-rigging multi-tasking environment. Also, if off-line computation is available in parallel to the animation, a finite element modeler should be included. However, inclusion of a finite element modeler hinders the possibility of a real-time animation which has been achieved for the sample case described in Section 4.3 and Appendices E and F.

This chapter has reviewed the work done throughout this thesis and research, has pointed out the recommended uses and significance of the dynamic behavior modeler, and has stated some potential future extensions to the modeler. The conclusion of the thesis is found below.

6.4 Conclusion

The increasing availability of high performance computers with fast 3-D graphics has made it possible to perform non-trivial physical simulations-and see the results-at fully interactive speeds. The current computer graphics and CAD technology, combined with engineering principles allows accurate physical modeling of rigid body dynamics.

In computer animation, there is a need to simulate the motions of objects by the physical principles of dynamics governing the motion in order to achieve a satisfactory degree of realism. Such a dynamic simulation capability is undoubtedly a requirement for multi-tasking motion planning for material handling in construction.

The dynamic behavior modeler presented in this thesis is conceptually modeled to perform dynamic simulation of 3-D rigid bodies for computer animation. The dynamic behavior modeler ensures a physically realistic environment. The modeler has the capability to predict the behavior of objects under dynamic loading within the environment. This capability provides a tool to analyze the dynamic responses of the objects to each other and to the environment.

The capabilities provided by the modeler is intended to be utilized within a multi-tasking motion planning system (MTMP) for material handling in construction. Nevertheless, there is a significant amount of work to be done to implement the dynamic behavior modeler and the MTMP system. Also, certain extensions and modifications need to be performed on WALKTHRU which is the platform for the implementation of the dynamic behavior modeler and the MTMP system. However, when completed, the dynamic behavior modeler component of the MTMP system will be of significance use and help for engineers to model material handling operations in construction. Moreover, the completion of the system will constitute an important step towards the automation of such operations.

The technology provided through the dynamic behavior modeler will ensure a reliable motion planning system. This helps engineers better plan, model, and control complex material handling operations. The engineers will evaluate the performance of these operations more efficiently. The natural outcome of the benefits of this technology will be the significant improvements in overall performance and constructability of the construction projects.

Appendix A
The Triangulation Algorithm

As discussed in Chapter 3, the method introduced by Lien and Kajiya (Lien and Kajiya 1984) has been found to be of the most use to incorporate the integral properties (mass properties) of the solids into WALKTHRU.

Due to the nature of the method, there is a need for a triangulation algorithm to dissect the faces of the polygons into triangles. The method's efficiency is improved through such triangulation algorithm. This appendix gives a brief information about the triangulation algorithm developed at Virginia Tech.

The triangulation algorithm for non-planar polygons was coded in C programming language. It was developed as a function for easy access from WALKTHRU. The input parameters to the function are the number of points of the polygon and the array containing the coordinates of the vertices. The output parameters are the number of triangles, and the array giving the list of vertices forming the triangles.

The triangulation algorithm was obtained by the following steps:

- Reducing the polygon to a planar polygon using either projection on a plane perpendicular to the average surface normal or by obtaining an approximate development of the non-planar polygon.
- Planar solution to be reached by using Greedy algorithm for triangulation of non-planar polygons. Solution consists of the following steps:

  - Getting a list of edges which contains all sides of the polygon and all lines connecting vertices of the polygon which are totally included within the polygon (This is checked by comparing interior angles with known polygon boundaries).
  - Ordering the edge list obtained in an ascending order as per length.
  - All boundaries of the polygon are edges for triangulation. Edges are picked from the order list to be edges of triangulation. If an edge intersects any previously defined edge, it is discarded.
  - After elimination is complete, the list of triangulation edges is obtained.
  - Triangulation is computed from edge list by proceeding along the vertex list.
- Extending the planar solution is to the non-planar polygon. The solution is consistent as the order of the vertices is maintained.
- The obtained triangulation is fast as there are no special considerations specified. The solution is neither minimum weight nor maximize minimum interior angles.

As mentioned earlier, the algorithm to compute integral properties is a function of the above described triangulation algorithm. The listing of the algorithm, written in C programming language will be presented in Appendix B.

Appendix B

The Listing of the Algorithm to Compute Integral Properties

This appendix presents the listing of the algorithm to calculate the integral properties (mass properties) of the solids.

The algorithm has been coded in C programming language on a Iris workstation. The algorithm is called within the triangulation algorithm which will be described in Appendix D. In other words, it is a function (or subroutine) of the triangulation algorithm.

As an input, the integ_prop (name of the algorithm as the function within triangulation program) receives the number of triangles (nt), the array giving the list of vertices forming the triangles and the coordinates of the triangles (3 x 3 x n), and the density of the solid. The algorithm computes the integral properties for each tetrahedron, and sums up these values for each separate solid. The output are the integral (mass) properties associated with each solid.

The following pages of this appendix presents the C listing of the algorithm.

```
/*

This program, integ_prop.c, computes the integral (mass)
properties of solids.  The function, integprop, is called
within a main program which executes a triangulation
algorithm.  The following listing is the C code for the
algorithm to calculate the integral properties.  Explanatory
comments are provided along with the code.

*/



/*   function to compute integral properties   */


integprop (nt, trianglelist, density, totalvolume, totalmass,
          totalI_xx, totalI_yy, totalI_zz,
          totalI_xy, totalI_xz, totalI_yz)


/*
     INPUT arguments:

nt: number of triangles, received from the main program

trianglelist: list of triangles, received from the main
information=>[x,y,z values][vertex number][triangle number]

density: density of the solid, received from the main
program, input by the user

     OUTPUT arguments:

total volume: summation of the volume of the tetrahedra

totalI_xx, totalI_yy, totalI_zz: summation of the mass
moments of inertia

totalI_xy, totalI_xz, totalI_yz: summation of the products of
inertia

totalmass: summation of the mass of tetrahedra

The output arguments are sent to the main program.
*/
```

```
/*   argument declaration */

float trianglelist[3][3][ ], density;
float *totalvolume, *totalI_xx, *totalI_yy, *totalI_zz,
      *totalI_xy, *totalI_xz, *totalI_yz,*totalmass;

int nt;

{


/*
volume: volume of each tetrahedron

C_x, C_y, C_z: x,y,z coordinates of center of gravity of each
tetrahedron

I_xx, I_yy, I_zz: mass moments of inertia for each
tetrahedron

I_xy, I_xz, I_yz: products of inertia for each tetrahedron

x, y, z: x, y, z coordinates of the vertices of each
tetrahedron received from main program

det: determinant of the transformation matrix

mass: mass of each tetrahedron
*/


/*   variable declaration */

float volume[ ], C_x[ ], C_y[ ], C_z[ ],
      I_xx[ ], I_yy[ ], I_zz[ ], I_xy[ ], I_xz[ ], I_yz[ ],
      x[3], y[3], z[3], det[ ], mass[ ];

int i, j, status;


/*   error check: if function returns 0 ==> success, if 1 ==>
     failure   */

     status=1;
```

```
/*   for loop to get the coordinate values for the vertices
     of each tetrahedron        */

     for   (i=0;i<nt;i++)            /*number of triangles*/

          {

               for   (j=0;j<3;j++)  /*vertex number*/

                    {

                    x[j]=trianglelist[0][j][i];
                    y[j]=trianglelist[1][j][i];     /*get
                                                    x,y,z*/
                    z[j]=trianglelist[2][j][i];

                    }

          /*find determinant of the transformation matrix*/

          det[i]=(x[0]*(y[1]*z[2]-y[2]*z[1]) -
                        x[1]*(y[0]*z[2]-y[2]*z[0]) +
                        x[2]*(y[0]*z[1]-y[1]*z[0]));



          /*find volume*/

          *totalvolume=0.;

          volume[i]=det[i]/6.;

          *totalvolume += volume[i];


          /*find center of mass*/

          C_x[i]=(x[0]+x[1]+x[2])/4.;

          C_y[i]=(y[0]+y[1]+y[2])/4.;

          C_z[i]=(z[0]+z[1]+z[2])/4.;
```

```
/*find mass moments of inertia*/

*totalI_xx=0.;
*totalI_yy=0.;
*totalI_zz=0.;


I_xx[i]=(x[0]*x[0] + x[1]*x[1] + x[2]*x[2] +
          x[0]*x[1] + x[0]*x[2] + x[1]*x[2]) *
          volume[i] / 10.;

I_yy[i]=(y[0]*y[0] + y[1]*y[1] + y[2]*y[2] +
          y[0]*y[1] + y[0]*y[2] + y[1]*y[2]) *
          volume[i] / 10.;

I_zz[i]=(z[0]*z[0] + z[1]*z[1] + z[2]*z[2] +
          z[0]*z[1] + z[0]*z[2] + z[1]*z[2]) *
          volume[i] / 10.;


*totalI_xx += I_yy[i]+I_zz[i];
*totalI_yy += I_xx[i]+I_zz[i];
*totalI_zz += I_xx[i]+I_yy[i];



/*find products of inertia*/

*totalI_xy=0.;
*totalI_xz=0.;
*totalI_yz=0.;


I_xy[i]=(2*(x[0]*y[0] + x[1]*y[1] + x[2]*y[2]) +
                (x[0]*y[1] + x[1]*y[0] + x[0]*y[2]
          +
                 x[2]*y[0] + x[1]*y[2] +x[2]*y[1]))
          *
             volume[i] / 20.;

I_xz[i]=(2*(x[0]*z[0] + x[1]*z[1] + x[2]*z[2]) +
                 (x[0]*z[1] + x[1]*z[0] + x[0]*z[2]
          +
                  x[2]*z[0] + x[1]*z[2]
               +x[2]*z[1])) *
             volume[i] / 20.;
```

```
        I_yz[i]=(2*(y[0]*z[0] + y[1]*z[1] + y[2]*z[2]) +
                          (y[0]*z[1] + y[1]*z[0]
                  + y[0]*z[2] +
                          y[2]*z[0] + y[1]*z[2] +
                       y[2]*z[1])) *
                     volume[i] / 20.;

        *totalI_xy += I_xy[i];
        *totalI_xz += I_xz[i];
        *totalI_yz += I_yz[i];


        /*find mass*/

        *totalmass=0.;

        mass[i]=volume[i] * density;

        *totalmass += mass[i];

        }

        status=0;

        return (status);

}
```

Appendix C

Deriving the Equations Of Motion

As mentioned in Chapter 4, Wittenburg (Wittenburg 1977) has been found to be of the most use in the conceptual development of the dynamic behavior modeler. The equations of motion are derived from D'Alembert's principle of virtual work (Wittenburg 1977), which states that if a system is in dynamic equilibrium and the bodies are allowed to move a small amount (called virtual displacement) then the sum of the work of applied forces, the work of applied torques, and the work of internal forces will be equal and opposite to the work of changes in momentum. This is equivalent to saying that all work done in the system is accounted for. For a system of **n** links, D'Alembert's equation is:

$$\sum_{i=0}^{n} [dr_i (F_i - m_i r_i'') + d\varnothing_i (M_i - L_i') + dW_i] = 0 \qquad \text{(C-1)}$$

• $dr_i (F_i - m_i r_i'')$ ==> work of applied forces minus work of changes in linear momentum

• $d\varnothing_i (M_i - L_i')$ ==> work of applied torques minus work of changes in angular momentum

• dW_i ==> work of internal forces

• 0 ==> none left over

where:

dr_i = virtual linear displacement of link number i (3-D coordinate)

F_i = total applied force through the center of gravity (COG) of link i (scalar)

m_i = the mass of the link i (scalar)

r_i, r'_i, r''_i = the linear position, velocity, and acceleration of link i (coord)

$d\phi_i$ = virtual angular displacement of link number i (coord)

M_i = total applied torque on link i (coord)

L'_i = the change in angular momentum of link number i (coord)

where $L'_i = I_i \cdot \phi''_i + \phi'_i \times I_i \cdot \phi'_i$

I_i = moment of inertia tensor of link i (3x3 matrix),

ϕ_i, ϕ'_i, ϕ''_i = the angular position, velocity, and acceleration of link i (coord)

* this component of the equation is further described in detail.

dW_i = virtual work done by internal forces on link i (coord) (i.e., the work done by springs and dampers in joint i)

D'Alembert's equation is written in terms of variables for position (r) and orientation (ϕ). If this is treated as a system of n independent linear equations, then each equation will have six unknowns: the linear acceleration in the x, y, and z directions (r''_x, r''_y, r''_z) and the angular acceleration about the three axes (ϕ''_x, ϕ''_y, ϕ''_z). All other variables are calculated as known quantities from the current state of the system, except for the virtual displacements, which are later eliminated from the equations. This gives a total of (6 * n) unknowns.

If, instead, D'Alembert's principle is expressed in terms of the system's degrees of freedom, the total number of unknowns is reduced to total number of degrees of freedom, $\mathbf{n}_{DOF}$, which is typically much less than (6 * n), because most links have parent joints with fewer than six degrees of freedom. If the number of unknowns is not reduced in this way, then (6 - $\mathbf{n}_{DOF}$) additional constraint equations would have to be written, one for each disallowed direction of motion. Thus, by formulating the equations in terms of the degrees of freedom, the number of unknowns are reduced and the simulation runs more efficiently. In addition, the resulting motion is expressed in terms of the joint degrees of freedom as they were constructed.

To express the motion of the system in terms of the degrees of freedom, four generalized coordinate vectors are used. Each vector has one entry for each degree of freedom:

	q	a vector of positions (either r or ø)
	q'	a vector of velocities
	q"	a vector of accelerations (unknowns)
and	dq,	a vector of virtual displacements.

Matrix equations describing each of the vector quantities dø, dr, ø", r", and dW in terms of generalized coordinates and other known quantities are derived:

$$d\phi = -T^T p^T dq \qquad (C\text{-}2)$$

$$dr = [p \times T\,(C + Z)T - kT]^T\ dq \qquad (C\text{-}3)$$

$$\text{ø}'' = -T^T \; (p^T q'' + f) + \text{ø}''_o \qquad \text{(C-4)}$$

$$r'' = [p \times T\,(C + Z)T - kT]^T \; q'' + U \qquad \text{(C-5)}$$

$$dW = -dq^T \,(k \,.\, X + p \,.\, Y) \qquad \text{(C-6)}$$

and the following new (known) terms are introduced:

T	= matrix expressing connectivity of the system
p	= matrix of the unit axes of rotation of all rotational degrees of freedom of the system (zero for translational degrees of freedom)
C	= matrix of distances from the joints to the centers of gravity of the links which they connect
Z	= matrix of current displacement vectors along translational axes of freedom (zero for rotational degrees of freedom)
k	= matrix of partial derivatives of relative translational vectors with respect to each translational degree of freedom
f	= matrix of values relating angular velocity of one degree of freedom to a resulting angular acceleration of another degree of freedom
$\text{ø}''_o$	= vector of coordinates each equal to angular acceleration of inertial frame of reference
U	= arrays of values, one per link, which relate its linear acceleration to known quantities in the system

X = vector of internal applied forces (one per degree of freedom)

Y = vector of internal applied torques (one per degree of freedom)

[details can be found in Wittenburg (Wittenburg 1977), pages 147-163]

All of these new terms above are calculated based on the pre-defined model of the system, the known values for q and q', and the current internally applied forces and torques.

The derivation continues by substituting equations (C-2) through (C-6) into equation (C-1) to yield:

$$\begin{aligned}
& dq^T \{ [p \times T (C + Z)T - kT] \\
& . \{F - m [p \times T (C + Z)T - kT]^T q'' - mU\} \\
& - pT . \{M - I . [-T^T (p^T q'' + f) + \phi'_o] - \phi' \times I . \phi'\} \\
& - k . X - p . Y \\
& \} = 0 \qquad \text{(C-7)}
\end{aligned}$$

Isolating the terms involving q'', the following expression is obtained:

$$dq^T (-A q'' + B) = 0 \qquad \text{(C-8)}$$

where

$$A = [p \times T\,(C + Z)T - kT] \,.\, m\,[p \times T\,(C + Z)T - kT]^T + (pT) \,.\, I \,.\, (pT)^T \qquad \text{(C-9)}$$

$$B = [p \times T\,(C + Z)T - kT] \,.\, (F - mU) - pT \,.\, [M + I \,.\, (T^T f - \phi'_o) - \phi' \times I \,.\, \phi'] - k \,.\, X - p \,.\, Y \qquad \text{(C-10)}$$

Since the motion of all generalized coordinates is independent, the dq term from equation (C-8) can be removed, yielding the original equation (4-3) (p. 94):

$$| A | \; | q'' | = | B |$$

Although the final form of the equations for A and B appear complicated, it should be stressed that all of the quantities are based on a relatively small set of very natural parameters (mass, size, type of joint, etc.). The only unknowns are q'', and the only required user inputs are F and M, the applied forces and torques.

A note on the coordinate system used: When forming the A matrix and B vector, it does not matter which coordinate system is used to represent vectors in 3-D space, as long as they are consistent. The final equation can be calculated in the inertial (world) reference frame. In many cases, as with axes of a joint and moment of inertia tensors, it is convenient to store the variables in local coordinates and convert them into inertial coordinates as they enter the equations.

The following sections describe the moment of inertia tensor and rotational dynamics concepts involved in the D'Alembert's equation.

Moment of Inertia Tensor

In the 3 x 3 matrix form of inertia tensor of an object, the diagonal elements or the *moment of inertia coefficients* are given by:

$$\mathbf{I}_{xx} = \int \rho\,(y^2 + z^2)\,dv$$
$$\mathbf{I}_{yy} = \int \rho\,(x^2 + z^2)\,dv \qquad \text{(C-11)}$$
$$\mathbf{I}_{zz} = \int \rho\,(x^2 + y^2)\,dv$$

and the off-diagonal elements or the *product of inertia* are given by:

$$\mathbf{I}_{xy} = \int \rho\,(x\,y)\,dv$$
$$\mathbf{I}_{xz} = \int \rho\,(x\,z)\,dv \qquad \text{(C-12)}$$
$$\mathbf{I}_{yz} = \int \rho\,(y\,z)\,dv$$

where the subscripts stand for the matrix indices, *p* is the density of the object, and the integral is over the volume of the object. The inertia tensor can be transformed to any coordinate frame. The matrix of the tensor transforms under a 3 x 3 orthogonal matrix **D** as a *similarity transform*:

$$\mathbf{I'} = \mathbf{D\ I\ D^T} \qquad \text{(C-13)}$$

where the superscript T stands for the matrix transpose. For the purpose of the rotational transform the matrix **D** is the direction cosine matrix of the two coordinates. For the translational transform, by the matrix form of the tensor (C-11) and (C-12):

$$\begin{aligned}
\mathbf{I'_{xx}} &= \mathbf{I_{xx}} + m\ (y^2 + z^2) \\
\mathbf{I'_{yy}} &= \mathbf{I_{yy}} + m\ (x^2 + z^2) \\
\mathbf{I'_{zz}} &= \mathbf{I_{zz}} + m\ (x^2 + y^2) \qquad \text{(C-14)} \\
\mathbf{I'_{xy}} &= \mathbf{I_{xy}} + m\ (x\ y) \\
\mathbf{I'_{xz}} &= \mathbf{I_{xz}} + m\ (x\ z) \\
\mathbf{I'_{yz}} &= \mathbf{I_{yz}} + m\ (y\ z)
\end{aligned}$$

where x, y, and z gives the translation of the coordinate frame and m is the mass of the object.

The above described elements of the inertia tensor can be computed by the algorithm presented in Chapter 3. The C code of the algorithm is provided in Appendix B.

Rotational Dynamics

The rotational dynamics is given by:

$$d\mathbf{L}/dt = \mathbf{M} \tag{C-15}$$

$$\mathbf{L} = \mathbf{I} \cdot \boldsymbol{\phi}' \tag{C-16}$$

where **L** is the angular momentum of the body, **M** is the external torque applied to the body, **I** is the moment of inertia tensor of the body, and **ø'** is the angular velocity of the body.

The major obstacle for a simple solution is that the rotational equivalent of mass, the moment of inertia tensor, is not constant with respect to an inertial reference frame but changes as the body rotates. This can be avoided by solving the rotational dynamics in a frame that is fixed in the body. Taking the time derivative of (C-15) with reference to a coordinate frame fixed in the body:

$$d\mathbf{L}/dt + \boldsymbol{\phi}' \times \mathbf{L} = \mathbf{M} \tag{C-17}$$

Substituting (C-16) into (C-17)

$$\mathbf{I} \cdot d\boldsymbol{\phi}'/dt + \boldsymbol{\phi}' \times (\mathbf{I} \cdot \boldsymbol{\phi}') = \mathbf{M} \tag{C-18}$$

If the principal axes are chosen as the fixed axes of the body and (C-18) is transformed to the body fixed coordinate, a set of simplified differential equations are obtained:

$$\begin{aligned} I_x \, \phi''_x + (I_z - I_y)\, \phi'_z \, \phi'_y &= M_x \\ I_y \, \phi''_y + (I_x - I_z)\, \phi'_x \, \phi'_z &= M_y \\ I_z \, \phi''_z + (I_y - I_x)\, \phi'_y \, \phi'_x &= M_z \end{aligned} \qquad \text{(C-19)}$$

where the products of inertia do not appear. These are known as the *Euler equations* (Goldstein 1950). The x, y, and z are the directions of the principal axes.

This appendix has introduced a brief derivation of the equations of motion based on D'Alembert's principle of virtual work. Within the dynamic behavior modeler, this principle is utilized to form the equations of motion.

Appendix D

Current Version of the "Path-Finder" System

This appendix describes the current "Path-Finder" system which was developed by Bechtel Corporation. The information provided is based on the paper written by Morad et al. (Morad et al. 1991).

The "Path-Finder" system finds the feasible path of an object from one position and orientation in a 3-D computer model to another position and orientation. It optimizes the path subject to motion constraints on mechanisms which manipulate the object. Also it ensures that there are no interferences along the path between the moving object and manipulation mechanisms and other objects in the environment.

The program operates within WALKTHRU. It utilizes AI concepts to find the feasible path for moving an object from an initial location to a desired location in the 3-D computer model. The following sections provide a brief description of the problem representation and the search control strategy used by the system to find a solution for the path problem.

D.1 Problem Environment Representation

The problem environment is formally represented by using the "State-Space Representation". The process of developing the state-space representation in "Path-Finder" is described as follows:

Definition of the Start State (Start Node):

The attributes of the start state are defined by the initial conditions of the problem. The initial position and orientation of the object to be moved and its manipulation mechanisms define the attributes of the start state. The initial position of the object is the position in the 3-D computer model from which the motion process is initiated as defined by the user. The attributes which define the start state are:

- Position (x, y, z) of the moving object
- Orientation (ϕ_x, ϕ_y, ϕ_z) of the moving object
- Position(s) (x, y, z) of the manipulation mechanism(s)
- Orientation(s) (ϕ_x, ϕ_y, ϕ_z) of the manipulation mechanism(s)
- Total cost associated with the start state.

Definition of the Goal State (End Node):

The attributes of the goal state are defined by the conditions of the desired solution. The final position and orientation of the moving object define the attributes of the goal state. The final position of the object is as defined in the static (original) configuration of the 3-D computer model. The attributes which define the goal state are:

- Position (x, y, z) of the moving object
- Orientation (ϕ_x, ϕ_y, ϕ_z) of the moving object at the final position.

Definition of the Operators (Actions):

The operators are the actions which transfer the position and orientation of the moving object and its manipulation mechanism from one state (parent node) to another state (new node). Each operator defines a step change in the direction of one degree of freedom (transitional or rotational). The step size is variable and it is a function of the relative distance between the current position of the moving object and the final position.

Accordingly, each state in the state-space represents a discrete position and orientation of the object in space. Successive states represent the position of the objects after many step changes in the direction of different degrees of freedom. The degrees of freedom are defined by the user from the WALKTHRU object motion menus. The user can define a unit cost for moving along each degree of freedom. The number of degrees of freedom depend on the configuration of the manipulation mechanisms. Also, the user can define different penalties (costs) for changing the direction of the degree of freedom between two successive steps.

D.2 The Objective Function

The objective of the search process is to find the most feasible collision-free path for moving the object from its initial position to the desired position. The objective function optimization is minimum total cost. The total cost for a specific state (node) in the search space is a function of two cost components: actual cost and estimated cost.

- Total Cost = Actual Cost + Estimated Cost
- The actual cost is the accumulated cost due to applying the operators from the start node.

  Actual Cost = Σ (applied operator cost) + Σ (change in direction cost)

- Change in direction cost is added when any two successive operators are not for the same degree of freedom.
- Estimated cost is a function of the distance between the current position of the current state and the desired position of the moving object as defined by the goal state.

D.3 The Search Strategy

The program uses the Generate-Test approach as the problem solving strategy. The search process starts from the start state (start node). The generator generates all possible successor states from the start state using the applicable operators (which represents the different degrees of freedom allowed by the manipulation mechanisms). The total cost of each generated node is calculated based on the cost of the applied operators, the direction of motion, and relative distance to the final position. All generated nodes are posted to a list called the open-list. For each generated node the following conditions are checked:

- If the node already exists in the open or closed lists
- If the position of the manipulation mechanisms are within the allowed motion limits

The next step is to select a node from the open-list which has the minimum total cost. Then the evaluator will check the following conditions:

- If the goal state is reached (by comparing the new position and orientation with the final position and orientation). The goal is achieved if the differences are within the accuracy levels defined by the user.

- If there is an interference between the moving object and other objects in the 3-D computer model as a result of moving the object by the manipulation mechanism to the position defined by the selected state.
- If there is an interference between the manipulation mechanism of the moving object and other objects in the 3-D computer model as a result of moving the object to the position defined by the selected state.

Future extensions of the system will incorporate several constraints which will be imposed on the search process. These extensions include: equipment integrity (tipping, etc.), control of object velocity, and safety of the manipulation process.

The search will stop if the final position is reached. If the final position has not been reached, the current node will be posted to the closed-list and a new set of nodes, which represent new states, will be generated from the current node. The new set of nodes will be posted to the open-list. In case of interference, the path will be terminated with no new nodes to be generated from the current node. The search process will be backtracked one level. Then, the generator will select a node from the open-list to continue the search process.

The described search strategy can be classified as a depth-first control search strategy with a data-driven reasoning direction. However, it is modified to consider the total cost as the criteria for selecting the next node in the search space from the open-list and not the level at which the node is created within the nodes hierarchy.

The output of the search process is a list of the nodes along the selected path. The position and orientation of the 3-D computer model objects at each node are saved in a record file. The record file contains frames of the objects' position and orientation at each node. This record file will be executed by the "Play Back" routine of WALKTHRU to visually simulate the generated path using the 3-D computer model of the facility.

Appendix E

Analytical Model of the Sample Case

This appendix presents the analytical model of the dynamics of a suspended load and the response of the crane's boom to this dynamic loading for each stage of the sample case discussed in Section 4.3.2.1. The development of the analytical model has been based on the assumptions which were listed also in Section 4.3.2.1.

The free body diagram of the dynamic system is shown in Figure E.1.

where:

$\phi =$	angle between load hoist rope and the vertical (angle of pendulum)
$L =$	length of the rope
$R =$	length of the boom
$W =$	weight of the load
$T =$	tensile force of the rope
$a_{cr} =$	acceleration of the crane
$a_{\phi} =$	acceleration of the load in ϕ axis
$g =$	gravity

When the crane moves with an acceleration, the derivation of the general form of the equation expressing the dynamic behavior of the suspended load is as follows:

$a_{\phi} = L\, \phi'' \mathbf{e}_{\phi} + a_{cr}\mathbf{i}$

$a_{cr}\mathbf{i} = a_{cr}\cos\phi\, \mathbf{e}_{\phi} + a_{cr}\sin\phi\, \mathbf{e}_{r}$

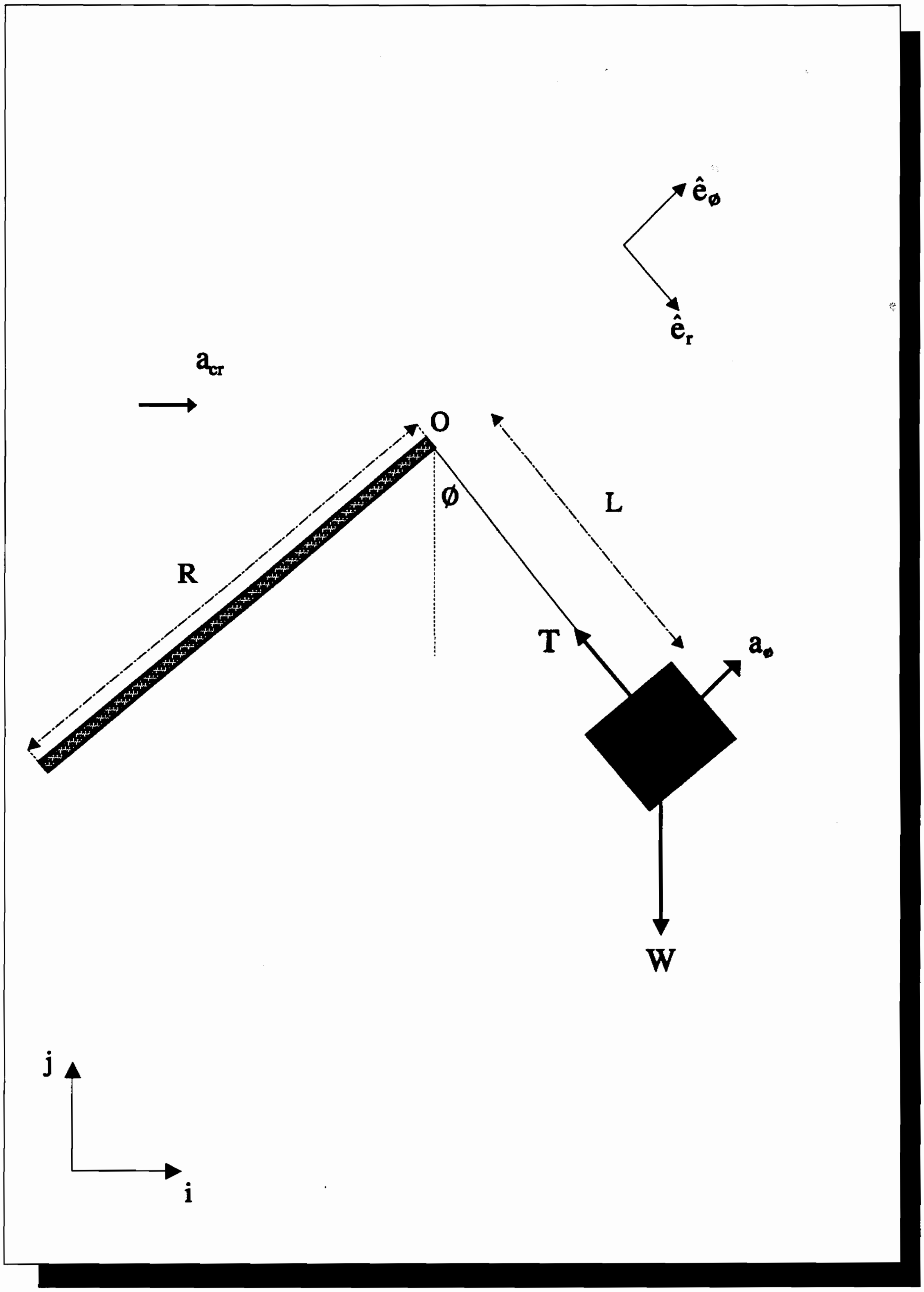


Figure E.1: Free Body Diagram of the System

Summation of forces in $\mathbf{e}_\phi$ axis is zero, hence:

$\sum F_{e\phi} = 0 \Longrightarrow -W\sin\phi + ma_\phi = 0$, where m is the mass of the load

Substitute a_ϕ:

$-W\sin\phi + (L\,\phi'' + a_{cr}\cos\phi)\,W/g = 0$, where g is the gravity

$\phi \Longrightarrow$ small, hence:

$-\phi + \phi''\,L / g + a_{cr} / g = 0$

Multiply every term by g / L:

$\phi'' = \phi\, g / L - a_{cr} / L$

For the differential equation:

$\phi(t) = \phi_h(t) + \phi_p(t)$

The particular solution is:

$\phi_p(t) = -a_{cr} / L$

The homogenous solution is:

$\phi_h(t) = A\cos((g/L)^{1/2}t)$

Set $\phi(0) = 0$:

$A = a_{cr} / L$

Therefore the solution of the $\phi(t)$ becomes:

$$\phi(t) = a_{cr} / L \cos((g/L)^{1/2}t) - a_{cr} / L \qquad \text{(E-1)}$$

The tension of the rope can be expressed as follows:

$W\cos\phi - T = m\,a\mathbf{e}_\mathbf{r}$

where $a\mathbf{e_r} = a_{cr}\sin\phi\mathbf{e_r} - (\phi')^2 / L\ \mathbf{e_r}$

Substituting the acceleration:

$W\cos\phi - W/g\ [a_{cr}\sin\phi - (\phi')^2 / L] - T = 0$

Then tension becomes:

$$T = W\ [(\phi')^2 / L\ g + \cos\phi + a_{cr}\sin\phi / g] \qquad \text{(E-2)}$$

When the crane is moving with constant velocity (no acceleration), the dynamic behavior of the suspended load can be expressed as follows:

$-W\sin\phi - m\ L\ \phi'' = 0$

$\phi + \phi''\ L / g = 0$

$\phi'' = -\ \phi\ g / L$

$\phi(t) = \phi_h(t) + \phi_p(t)$

where $\phi_p(t)$ (particular solution) = 0 and

$\phi_h(t)$ (homogenous solution) = $A\ \sin((g/L)^{1/2}t) + B\ \cos((g/L)^{1/2}t)$

Set $\phi(0) = \phi_c$:

$B = \phi_c$ (final position of the last stage)

Set $\phi'(o) = \phi'_c$:

$A = \phi'_c\ (L/g)^{1/2}$ (final velocity of the last stage)

Hence the final equation becomes:

$\phi_h(t) = \ \phi'_c\ (L/g)^{1/2}\ \sin((g/L)^{1/2}t) + \phi_c\ \cos((g/L)^{1/2}t)$

The equation expressing the tensile force in the rope is as follows when the crane has no acceleration:

$T = W [(\emptyset')^2 / L\, g + \cos\emptyset]$

In case of rotation of the boom, the load pendulates in an additional plane. Figure E.2 depicts the rotation case where:

$\theta =$	rotation angle
$\varphi =$	angle between the rope and the vertical (angle of pendulum in the rotation plane)
$a_r =$	radial acceleration
$a_t =$	tangential acceleration

The equations which express the rotation case are as follows:

$a = (a_r\cos\theta(t) - a_t\sin\theta(t))\mathbf{i} + (a_r\sin\theta(t) + a_t\cos\theta(t))\mathbf{j}$

where:

$a_r = (\theta')^2 / R$

$a_t = R\, \theta''$

Having the forces in equilibrium:

$\frac{w}{g} a\cos\phi L - w \sin\phi L = \frac{w}{g} \phi'' L^2$

Angle ϕ is small and hence:

$a - g\phi = L\phi''$

The equation becomes:

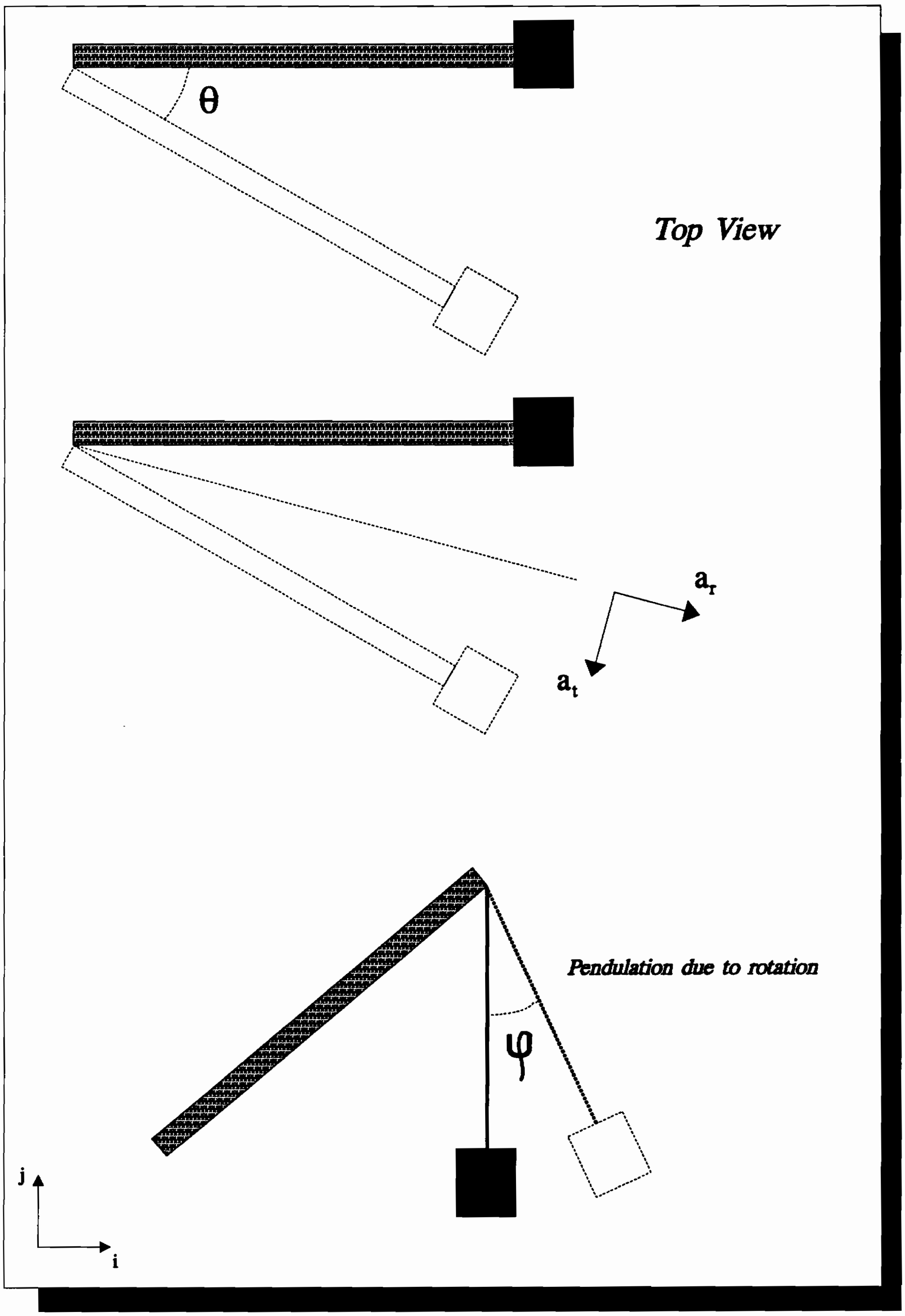


Figure E.2: Rotation Parameters

$\frac{a}{L} = \phi'' + \frac{g}{L}\phi$

The same equations are applicable for the pendulating motion in the rotation plane; hence:

$\frac{a}{L} = \varphi'' + \frac{g}{L}\varphi$

Substituting a_r and a_t in these equations, the following differential equations are obtained:

$$\frac{(\theta')^2}{RL}\cos\theta(t) - \frac{R\,\theta''}{L}\sin\theta(t) = \phi'' + \frac{g}{L}\phi \qquad \text{(E-3)}$$

$$\frac{(\theta')^2}{RL}\sin\theta(t) + \frac{R\,\theta''}{L}\cos\theta(t) = \varphi'' + \frac{g}{L}\varphi \qquad \text{(E-4)}$$

The solution is in the form of:

$\phi = \phi_h + \phi_p$ for ϕ, and $\varphi = \varphi_h + \varphi_p$ for φ

For the homogenous solution:

$\phi_h = A\sin((g/L)^{1/2}t) + B\cos((g/L)^{1/2}t)$

where:

$\theta_{initial} = \theta(0) = \phi_{initial} = \Rightarrow B$ (last stage's final) and

$\theta'_{initial} = \theta'(0) = \phi'_{initial} \Longrightarrow A = \phi'_c(L/g)^{1/2}$ (ϕ'_c is last stage's final)

The above expressions are also true for φ_h.

For the particular solutions, the equations are expressed through Taylor series (Kreyszig 1979):

$$\cos\theta(t) = \sum_{n=0}^{\infty} (-1)^n \frac{(t)^{2n}}{(2n)!}$$

$$\sin\theta(t) = - \sum_{n=0}^{\infty} (-1)^n \frac{(t)^{2n+1}}{(2n+1)!}$$

For particular solution, the cosine and sine terms in equations (E-3) and (E-4) can be expressed respectively as follows:

$$C_n \sum_{n=0}^{m} (-1)^n \frac{(t)^{2n}}{2n!} = \sum_{n=2}^{N} n(n-1)\, A_n\, t^{n-2} + \frac{g}{L} \sum_{n=0}^{N} A_n\, t^n$$

$$- C_n \sum_{n=0}^{m} (-1)^n \frac{(t)^{2n+1}}{(2n+1)!} = \sum_{n=2}^{N} n(n-1)\, A_n\, t^{n-2} + \frac{g}{L} \sum_{n=0}^{N} A_n\, t^n$$

where:

$m =$ 2

$N =$ $4n+1$

$C_n =$ $A_{n+2}(n+2)(n+1) + A_n\, g / L$ (C_n has a value other than zero for even exponents)

angle of rotation, θ can be represented as $kt^2/2$ ($\theta' = kt$ and $\theta'' = k$), where k is a constant.

Figure E.3 helps to determine the equation expressing the tension in case of rotation:

$a^2 + b^2 = c^2$

where:

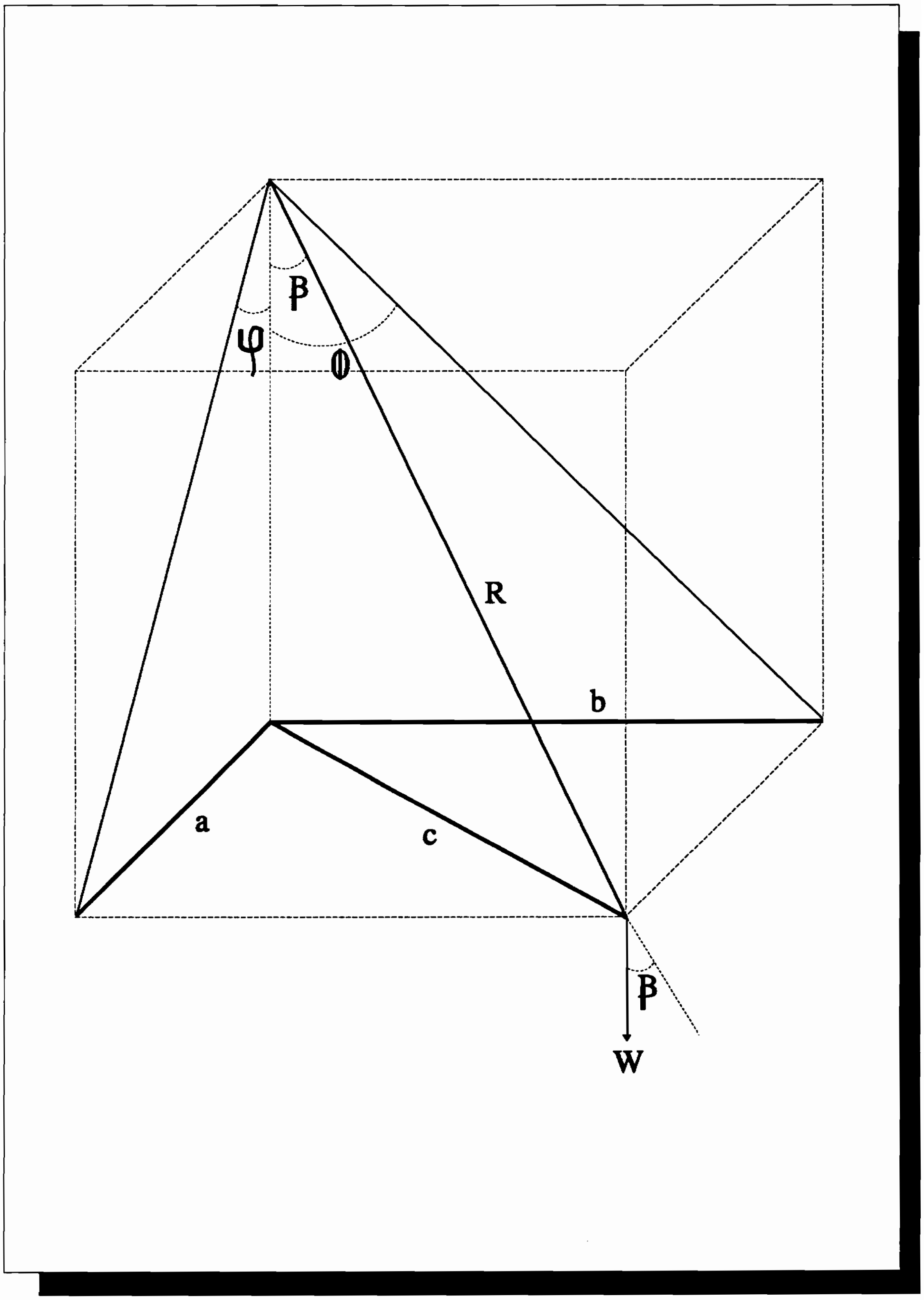


Figure E.3: Parameters to Compute Tension in Case of Rotation

$a = R \sin\varphi$ and $b = R \sin\phi$

Hence:

$c = \sqrt{a^2 + b^2} \Longrightarrow R\sqrt{\sin^2\varphi + \sin^2\phi}$

To determine angle $\cos\beta$:

$\cos\beta = \sqrt{1 - \sin^2\beta}$

$\sin\beta = \dfrac{R\sqrt{\sin^2\varphi + \sin^2\phi}}{R} \Longrightarrow \sqrt{\sin^2\varphi + \sin^2\phi}$

$\cos\beta$ becomes:

$\cos\beta = \sqrt{1 - \sin^2\varphi - \sin^2\phi}$

The tensile force in case of rotation can be expressed as follows:

$$T = \frac{W}{g}\frac{(\phi')^2}{L} + \frac{W}{g}\frac{(\varphi')^2}{L} - \frac{W}{g}[a_r\cos\theta(t) - a_t\sin\theta(t)] - \frac{W}{g}[a_r\sin\theta(t) + a_t\cos\theta(t)] + W\sqrt{1 - \sin^2\varphi - \sin^2\phi} \qquad \text{(E-5)}$$

The response of the boom to the dynamic loading can be determined through the equation given below (Meirovitch 1975).

$v(x,t) = \varnothing_r(x)\, Q_r(t)$

where:

$v(x,t)$ is the displacement along the beam

$\varnothing_r(x)$ is the shape function and expresses the natural modes as follows:

$\varnothing_r(x) = \sqrt{\dfrac{2}{ml}}\sin\dfrac{r\pi x}{l}$ where $r = 1,2,\ldots$, m is mass and l is length of the beam

$Q_r(t)$ is the generalized forces and expressed as follows:

$$Q_r(t) = \int_0^1 f(x,t)\, \varnothing_r(x)\, dx, \qquad r = 1,2,...$$

where f(x,t) is the distributed forcing function.

The general response can be obtained by combining these equations:

$$v(x,t) = \sum_{r=1}^{\infty} \varnothing_r(x) \left[\frac{1}{w_r} \int_0^t Q_r(\tau) \sin w_r(t-\tau)\, d\tau + q_{ro} \cos w_r t + \frac{q'_{ro}}{w_r} \sin w_r t \right]$$

where:

w_r is the natural frequency of the beam and

q_{ro} and q'_{ro} are the initial conditions and can be expressed as follows:

$$q_{ro} = \int_0^1 m v_o(x) \varnothing_r(x)\, dx, \qquad r = 1,2,...$$

$$q'_{ro} = \int_0^1 m v'_o(x) \varnothing_r(x)\, dx, \qquad r = 1,2,...$$

The expression v(x,t) is a dynamic response which computes the displacements with respect to time. However, such a computation requires considerable programming time and is not within the scope of this thesis. Also, the natural frequencies of the load and the boom in the sample case are not close enough to demand a computation for the dynamic response of the boom. The natural frequency (first vibration mode) of a cantilever beam is expressed as follows (Clough and Penzien 1975):

$$\omega_n = (1.875)^2 \sqrt{\frac{EI}{mR^4}}$$

For a small mobile crane boom, the values of the parameters are as follows (Ito et al. 1978):

E, modulus of longitudinal elacticity (kg/cm^2) = 2.1 x 10^6

I, geometrical moment of inertia (cm^4) = 3.47 x 10^4

W, weight of the boom (kg) = 1014, (==> m, mass = 1014/9.8)

R, length of the boom (m) = 15.24

Substituting these values into the equation, the natural frequency, ω_n is found as 0.402 (r/s).

For the load the natural frequency can be expressed as follows (Meirovitch 1975):

$\omega_n = (g / L)^{1/2}$, where L is the length of the rope and is 10.5 meters (for boom angle of 45^0 in case of a small mobile crane) (Ito et al. 1978).

The natural frequency for load is calculated to be 0.968 (r/s). This value is more than twice of the boom's value.

Hence, the displacements on the boom are determined statically through the equation given below (Paz 1985).

$$v(x) = \frac{FR^3}{3EI}\left(1 - \cos\frac{\pi x}{2R}\right) \qquad \text{(E-6)}$$

where:

F is the force

EI is the flexural rigidity of the boom and

R is the length of the boom.

This appendix provides the discussion of equations for the dynamic behavior of the suspended load and the response of the crane's boom to this dynamic loading. These equations have been coded and incorporated in a GL program for each stage of the pick and place task described in Section 4.3.2.1. The GL program is presented in Appendix F.

Appendix F
Source Code of the GL Program

This appendix presents the source code of the Graphics Language (GL) program written for the sample case discussed in Section 4.3 and Appendix E. The sample case program consists of the following functions:

- Main program
- Compprop, to compute integral properties of solids
- Drawmodel, to display the animation
- Genframe, to generate the object frames
- Showframe, to draw the specified objects
- Initgraph, to perform GL drawing
- Newint, to compute the new integral properties of solids

Explanatory comments are provided within the code for each function. The functions were coded in C programming language, and GL functions were used to obtain the required graphics for the animation. The coding and the animation were performed on a Silicon Graphics Iris 4D/80GT workstation.

Sample Case (mtmp c)

```
/* Main program */

/* Written by Shrikant Dixit */

#include <stdio.h>

extern comp_prop( );
extern draw_model( );

/* declare global variables for mass properties (upto 10 objects) */

float obj_vol[10],obj_ixx[10],obj_iyy[10],obj_izz[10],obj_ixy[10],obj_ixz[10],
      obj_iyz[10],obj_den[10],obj_mass[10];
int   total_obj;
float xshift,yshift,xxshift,zzshift;

/* declare global variables for model geometry */

float obj_points[6][1500][3],disp_list[6][1500][3];
int   obj_polylist[6][800][100],total_obj_points[10],total_obj_poly[10];
int   points_per_poly[6][800];

main( )
{
FILE *name;
int i,j;

    xshift = 0.0;
    yshift = 600.0;

    /* set mass properties and point and polygon count to zero */

    for( i=0;i<10;i++)
    {
        obj_vol[i] = 0.0;
        obj_ixx[i] = 0.0;
        obj_iyy[i] = 0.0;
        obj_izz[i] = 0.0;
        obj_ixy[i] = 0.0;
        obj_ixz[i] = 0.0;
        obj_iyz[i] = 0.0;
        obj_den[i] = 1.0;
        obj_mass[i] = 0.0;
        total_obj_points[i] = 0.0;
        total_obj_poly[i] = 0.0;
    }


    name = fopen("truck2.asc","r");
    comp_prop(name);

/* write out global properties */
/*
    for( i=0;i<total_obj;i++)
    {
        printf("\n volume of object %d is %f",i+1,obj_vol[i]);
        printf("\n ixx    of object %d is %f",i+1,obj_ixx[i]);
        printf("\n iyy    of object %d is %f",i+1,obj_iyy[i]);
        printf("\n izz    of object %d is %f",i+1,obj_izz[i]);
        printf("\n ixy    of object %d is %f",i+1,obj_ixy[i]);
        printf("\n ixz    of object %d is %f",i+1,obj_ixz[i]);
        printf("\n iyz    of object %d is %f",i+1,obj_iyz[i]);
        printf("\n mass   of object %d is %f",i+1,obj_mass[i]);
    }
*/

    /* assign display list */

    for( i=0;i<6;++i)
    {
        for( j=0;j<total_obj_points[i];++j)
        {
            disp_list[i][j][0] = obj_points[i][j][1];
            disp_list[i][j][1] = obj_points[i][j][2];
            disp_list[i][j][2] = obj_points[i][j][0];
         }
    }
```

```
   /* go into interactive mode and draw the crane */

   (void)draw_model(name);

for(i=0;i<total_obj;++i)
{/*
 for(j=0;j<total_obj_points[i];++j)
 {
    printf("\n objpoints[%d][%d][0] = %f",i,j,obj_points[i][j][0]);
    printf("\n objpoints[%d][%d][1] = %f",i,j,obj_points[i][j][1]);
    printf("\n objpoints[%d][%d][2] = %f",i,j,obj_points[i][j][2]);
 }
 printf("\n total polygons are %d",total_obj_poly[i]);
 for(j=0;j<total_obj_poly[i];++j)
 {
    printf("\n objpoints[%d][%d][0] = %d",i,j,obj_polylist[i][j][0]);
    printf("\n objpoints[%d][%d][1] = %d",i,j,obj_polylist[i][j][1]);
    printf("\n objpoints[%d][%d][2] = %d",i,j,obj_polylist[i][j][2]);
 }*/
}
}
```

Sample Case (compprop c)

```
/* This program uses integprop.c to compute mass properties
   of a WALKTHRU ASC II file */

/* written by : Shrikant Dixit */

#include <stdio.h>
#include <math.h>

extern int integprop( );
extern int open_polygon( );
extern int triangulate( );


extern float obj_vol[10],obj_ixx[10],obj_iyy[10],obj_izz[10],obj_ixy[10],
             obj_ixz[10],obj_iyz[10],obj_den[10],obj_mass[10];
extern int   total_obj;
extern float obj_points[6][1500][3];
extern int   obj_polylist[6][800][100],total_obj_poly[10],
             total_obj_points[10],points_per_poly[6][800];

/* start of function */

int comp_prop(fname)
FILE *fname;

{
    int obj_no,vol_no,numpoly,numpts,numtri,bnd_pts;
    int nt,triang[500][3],iostat,vertex;
    int j1,j2,j3,j4,j5,j6,j7,i,j,k,l,m;
    float points[500][3],bndry_list[50][3],trilist[3][3][500];
    float f1,f2,f3,density,volume,Ixx,Iyy,Izz,Ixy,Ixz,Iyz,mass;

    iostat = 0;
    vol_no = 0;

    while(iostat!=EOF)
    {
        iostat = fscanf(fname,"\n %d  %d %d %d %d %d %d %d %d %d \n",
                &numpoly,&numpts,&j1,&j2,&j3,&j4,&j5,&j6,&j7,&obj_no);
        if(iostat==EOF)
            break;

        /* read data */
        if (j5==5)
        {
            numtri = 0;
            ++vol_no;
            for(i=0;i<numpts;++i)
            {
                fscanf(fname,"\n %f %f %f",&f1,&f2,&f3);
                points[i][0] = f1;
                points[i][1] = f2;
                points[i][2] = f3;

                obj_points[obj_no - 1][total_obj_points[obj_no
                - 1]+i][0] = f1;
                obj_points[obj_no - 1][total_obj_points[obj_no
                - 1]+i][1] = f2;
                obj_points[obj_no - 1][total_obj_points[obj_no
                - 1]+i][2] = f3;

            } /* end for over i */

            /* update number of points added to model geometry */

            total_obj_points[obj_no - 1] += numpts;

            /* get all the faces of the volume, triangulate them and compile
               trilist and process using integprop */

            for(i=0;i<numpoly;i++)
            {
                fscanf(fname,"\n %d ",&bnd_pts);

                for(j=0;j<bnd_pts;j++)
                {
                    fscanf(fname," %d ",&vertex);
                    for(k=0;k<3;++k)
                        bndry_list[j][k] = points[vertex-1][k];

                    /* add the polygon to the global list */
                    obj_polylist[obj_no - 1][total_obj_poly[obj_no - 1]
                    + i][j] = total_obj_points[obj_no - 1] - numpts + vertex;

                } /* end for over j */

                /* record the points per polygon value */
                points_per_poly[obj_no -1][total_obj_poly[obj_no - 1]
                + i] = bnd_pts;

                /* get triangles */
                nt = 0;
                for(j=0;j<bnd_pts-3;++j)
                {
                    triang[nt][0] = 1;
                    triang[nt][1] = j+2;
                    triang[nt][2] = j+3;
                    ++nt;
                }

                for(j=0;j<nt;++j)
                {
                    for(k=0;k<3;++k)
                    {
                         for(l=0;l<3;++l)
                         {
                            trilist[l][k][numtri+j] =
                            bndry_list[(triang[j][k]-1)][l];
                         }
                    } /* end for over k */

                } /* end for over j */

                numtri += nt;
            } /* end for over i */

            /* update the object polygon count */
            total_obj_poly[obj_no - 1] += numpoly;

            /* compute mass properties for the triangulated volume */

            density = obj_den[obj_no - 1];

            (void)integprop(numtri,trilist,density,&volume,&Ixx,&Iyy,
                                    &Izz,&Ixy,&Ixz,&Iyz,&mass);

            /* put mass properties in their global slots */
            obj_vol[obj_no - 1] += volume;
            obj_ixx[obj_no - 1] += Ixx;
            obj_iyy[obj_no - 1] += Iyy;
            obj_izz[obj_no - 1] += Izz;
            obj_ixy[obj_no - 1] += Ixy;
            obj_ixz[obj_no - 1] += Ixz;
            obj_iyz[obj_no - 1] += Iyz;
            obj_mass[obj_no - 1] += mass;
            total_obj = obj_no;
/* printf("\n obj no after computing is %d",total_obj);
printf("\n \n obtained vaules for mtmp are:");
        printf("\n volume is %f",volume);
        printf("\n Ixx    is %f",Ixx);
        printf("\n Iyy    is %f",Iyy);
        printf("\n Izz    is %f",Izz);
        printf("\n Ixy    is %f",Ixy);
        printf("\n Ixz    is %f",Ixz);
        printf("\n Iyz    is %f",Iyz);
        printf("\n mass   is %f",mass); */
        } /* endif condition over j5 */
    } /* end while condition over EOF */

    return(0);
}
/* end of function */
```

Sample Case (drawmodel c)

```
/* This function initializes graphics, sets up menus and then draws
the model. This function also animates the dynamic behavior of the
suspended load and the response of the crane's boom to this dynamic
loading. */

/* Written by Taylan Dal */

#include <stdio.h>
#include <gl.h>
#include <device.h>
#include <math.h>

#define PI 3.141593
#define g 9.8
#define E 21000000000
#define I 0.000347
#define W 2300.0
#define R 15.24
#define L 5.25
#define acc_crane_1 0.08
#define acc_crane_2 -0.08
#define v 0.00136


extern init_graphics();
extern draw_objects();
extern truck_motion();
extern boom_rotate();
extern generate_frame();

extern int total_obj;
extern float xshift,xxshift,zzshift;

int draw_model()
{
    float shift,dist,time,baseaxis[3],boomaxis[3],origin[3];
    float gamma,theta,delta,beta,boom_deflect[2],turn,dip;
    float l_gamma,l_theta,l_delta,l_beta,l_shift,l_bd[2];
    float i_gamma,i_theta,i_delta,i_beta,i_shift,i_bd[2];
    float tension,ang_vel,inst_time;
    float s2_fin_delta,s2_fin_ang_vel,s3_fin_delta,s3_fin_ang_vel;
    float s4_fin_delta,s4_fin_ang_vel,s5l_fin_beta,s5l_fin_ang_vel;
    float s52_fin_beta,s52_fin_ang_vel;
    int i,frames,att_status;

    init_graphics();

    frontbuffer(TRUE);
    clear();
    frontbuffer(FALSE);

    /* draw the initial condition of the model */
    shift = 0.0;
    gamma = 0.0;
    theta = 0.0;
    delta = 0.0;
    beta = 0.0;
    att_status = 0;
    boom_deflect[0] = 0.0;
    boom_deflect[1] = 0.0;
    generate_frame(shift,gamma,theta,delta,beta,boom_deflect,att_status);


    /* execute motion */
    dist = 121.8407267;
    time = 5.0;
    frames = 5;
    for (i=1;i<(time*frames +1);++i)
    {
        shift = (dist / (time * frames));
        generate_frame(shift,gamma,theta,delta,beta,boom_deflect,att_status);
    }
    shift = 0.0;


    /* rotate the boom */
    dip = 8.0555267;
    dip = dip * PI /180;
    for (i=1;i<(time*frames +1);++i)
    {
        theta = (dip / (time * frames));
        delta = -1.0 * theta;
        generate_frame(shift,gamma,theta,delta,beta,boom_deflect,att_status);
    }
    theta = 0.0;
    delta = 0.0;

    att_status = 1;

    /* lift the object */
    tension = W / sqrt(2.0);
    boom_deflect[1] = tension * R * R * R  / (3. * E * I);

    boom_deflect[0] = tension * R * R * R  / (24. * E * I);
    dip = -8.0555267;
    dip = dip * PI /180;
    i_bd[0] = 2.0 * boom_deflect[0] / (time * frames);
    i_bd[1] = 2.0 * boom_deflect[1] / (time * frames);
    for (i=1;i<(time*frames +1);++i)
    {
        if(i>(time*frames / 2))
        {
            i_bd[0] *= -1.0;
            i_bd[1] *= -1.0;
        }
        theta = (dip / (time * frames));
        delta = -1.0 * theta;
        generate_frame(shift,gamma,theta,delta,beta,i_bd,att_status);
    }

    l_bd[0] = boom_deflect[0];
    l_bd[1] = boom_deflect[1];

    theta = 0.0;
    delta = 0.0;


/* The following section of the program is to predict and display the
   dynamic behavior of the load and the response of the crane's boom to
   this dynamic loading */


dist = 100.0;
time = 50.0;
frames = 1;

l_gamma =0.0;
l_theta =0.0;
l_delta =0.0;
l_beta =0.0;
l_shift =0.0;

for (i=1; i<(time*frames +1); ++i)
{

   inst_time = i / (frames);


/* crane moving with acc (+) */


delta = (acc_crane_1 / L) * cos(sqrt(g/L)*inst_time) - acc_crane_1/L;
i_delta = l_delta - delta;
l_delta = delta;

i_shift = (dist / (time*frames));

shift = 0.5 * acc_crane_1 * inst_time * inst_time;
i_shift = shift - l_shift;
l_shift = shift;

ang_vel = - (acc_crane_1/L) * sqrt(g/L) * sin(sqrt(g/L)*inst_time);

tension = W * (ang_vel * ang_vel / L / g + cos(delta) +
               acc_crane_1 * sin(delta) / g);

boom_deflect[1] = tension * R * R * R * (1 - cos(90.*PI/180.0)) / (3. * E * I);

boom_deflect[0] = tension * R * R * R * (1 - cos(90.*PI/360.0)) / (3. * E * I);

i_bd[0] = boom_deflect[0] - l_bd[0];
l_bd[0] = boom_deflect[0];
```

```
i_bd[1] = boom_deflect[1] - l_bd[1];
l_bd[1] = boom_deflect[1];

   if (i == frames)
      {
       s2_fin_delta = delta;

       s2_fin_ang_vel = ang_vel;
      }

generate_frame(i_shift,gamma,theta,i_delta,beta,i_bd,att_status);

}


/* crane moving with no acc (0) */


dist = 100.0;
time = 25.0;
frames = 1;

l_gamma =0.0;
l_theta =0.0;
l_delta =0.0;
l_beta =0.0;
l_shift =0.0;

for (i=1; i<(time*frames +1); ++i)
{

   inst_time = i / frames;


delta = (s2_fin_ang_vel * sqrt(L/g) * sin(sqrt(g/L)*inst_time) +
             s2_fin_delta * cos(sqrt(g/L)*inst_time));

i_delta = delta - l_delta;
l_delta = delta;
i_shift = (dist / (time * frames));

ang_vel = s2_fin_ang_vel * sqrt(L/g) * sqrt(g/L) * cos(sqrt(g/L)*inst_time) -
          s2_fin_delta * sqrt(g/L) * sin(sqrt(g/L)*inst_time);

tension = W / g * (ang_vel * ang_vel / L) + W * cos(delta);

boom_deflect[1] = tension * R * R * R * (1 - cos(90.*PI/180.0)) / (3. * E * I);

boom_deflect[0] = tension * R * R * R * (1 - cos(90.*PI/360.0)) / (3. * E * I);

i_bd[0] = boom_deflect[0] - l_bd[0];
l_bd[0] = boom_deflect[0];
i_bd[1] = boom_deflect[1] - l_bd[1];
l_bd[1] = boom_deflect[1];

   if (i == frames)
      {
       s3_fin_delta = delta;

       s3_fin_ang_vel = ang_vel;
      }

generate_frame(i_shift,gamma,theta,i_delta,beta,i_bd,att_status);

}


/* crane moving with acc (-) */


dist = 100.0;
time = 50.0;
frames = 1;

l_gamma =0.0;
l_theta =0.0;
l_delta =0.0;
l_beta =0.0;
l_shift =0.0;

for (i=1; i<(time*frames +1); ++i)
{

   inst_time = i / frames;
```

```
delta = ((s3_fin_delta - acc_crane_2 / L) * cos(sqrt(g/L)*inst_time) -
              acc_crane_2 / L);

i_delta = delta - l_delta;
l_delta = delta;
i_shift = (dist / (time*frames));

shift = 4.0 * inst_time  + 0.5 * acc_crane_2 * inst_time * inst_time;
i_shift = shift - l_shift;
l_shift = shift;

ang_vel = -(s3_fin_delta - acc_crane_2 / L) * sin(sqrt(g/L)*inst_time)*
           sqrt(g/L);

tension = W * (ang_vel * ang_vel / (L / g) + cos(delta) +
              acc_crane_2 * sin(delta) / g);

boom_deflect[1] = tension * R * R * R * (1 - cos(90.*PI/180.0)) / (3. * E * I);

boom_deflect[0] = tension * R * R * R * (1 - cos(90.*PI/360.0)) / (3. * E * I);

i_bd[0] = boom_deflect[0] - l_bd[0];
l_bd[0] = boom_deflect[0];
i_bd[1] = boom_deflect[1] - l_bd[1];
l_bd[1] = boom_deflect[1];

generate_frame(i_shift,gamma,theta,i_delta,beta,i_bd,att_status);

}

/* crane stops, boom rotates (15) with angular acc, v (+) */


    shift = 0.0;
gamma = PI / 12.0;
time = 75.0;
frames = 1;

l_gamma =0.0;
l_beta =0.0;
i_bd[0] =0.0;
i_bd[1] =0.0;


for (i=1; i<(time*frames +1); ++i)
{

   inst_time = i / frames;
   i_gamma = gamma / (time*frames);


zzshift = (600.0 - xshift) * sin(i_gamma * i);



beta = pow(inst_time,12) * pow(v, 7) / (3840.*R*g) -

(11.* pow(inst_time, 10)*pow(v, 7)*L/(320.*R*g*g)) +

pow(inst_time, 8)*pow(v, 5)*(g*g*(R*R-8.)+1188.*v*v*
   L*L)/(384.*R*g*g*g) +

pow(inst_time, 6)*pow(v, 5)*(7.*g*g*L*(8.-R*R)-
   8316.*v*v*L*L*L)/(48.*R*g*g*g*g) +

pow(inst_time, 4)*pow(v, 3)*(g*g*g*g*(4.-R*R)+
   41580.*v*v*v*v*L*L*L*L+35.*v*v*g*g*L*L*(R*R-8.))/(8.*R*g*g*g*g*g) +

(inst_time*inst_time*v*v*v)*(105.*v*v*g*g*L*L*L*(8.-R*R)+3.*g*g*g*g*L*(R*R-4.)-
   124740.*v*v*v*v*L*L*L*L*L)/(2.*R*(pow(g, 6))) +

v*(3.*v*v*g*g*g*g*L*L*(8.-R*R)+105.*v*v*v*v*g*g*L*L*L*L*(R*R-16.)+
   2.*R*R*(pow(g, 6))+249480.*(pow(v, 6))*
   (pow(L, 6)))/(2.*R*(pow(g, 7)))   +

(s4_fin_ang_vel * sqrt(L/g) * sin(sqrt(g/L)*inst_time) +
   s4_fin_delta * cos(sqrt(g/L)*inst_time));

ang_vel = pow(inst_time, 11)*pow(v, 7)/(320.*R*g) +

-(11.*pow(inst_time, 9)*pow(v, 7)*L/(32.*R*g*g)) +

pow(inst_time, 7)*pow(v, 5)*(g*g*(R*R-8.)+1188.*v*v*
   L*L)/(48.*R*g*g*g) +

pow(inst_time, 5)*pow(v, 5)*(7.*g*g*L*(8.-R*R)-
   8316.*v*v*L*L*L)/(8.*R*g*g*g*g) +
pow(inst_time, 3)*pow(v, 3)*(g*g*g*g*(4.-R*R)+
   41580.*v*v*v*v*L*L*L*L+35.*v*v*g*g*L*L*(R*R-8.))/(2.*R*g*g*g*g*g) +

(inst_time*v*v*v)*(105.*v*v*g*g*L*L*L*(8.-R*R)+3.*g*g*g*g*L*(R*R-4.)-
   124740.*v*v*v*v*L*L*L*L*L)/(R*(pow(g, 6))) +

s4_fin_ang_vel * sqrt(L/g) * sqrt(g/L) * cos(sqrt(g/L)*inst_time) -
   s4_fin_delta * sqrt(g/L) * sin(sqrt(g/L)*inst_time);


tension = (W/g) * (ang_vel*ang_vel/L - v*time*v*time/R*(cos(v*time*time/2) +
          sin(v*time*time/2)) + v*R*(sin(v*time*time/2) - cos(v*time*time))) +
          W * sqrt(1.-(sin(beta)*sin(beta)));

boom_deflect[1] = tension * R * R * R * (1 - cos(90.*PI/180.)) / (3. * E * I);

boom_deflect[0] = tension * R * R * R * (1 - cos(90.*PI/360.)) / (3. * E * I);

   if (i == (time*frames))
      {
       s51_fin_beta = beta;

       s51_fin_ang_vel = ang_vel;
      }

i_beta = beta - l_beta;
l_beta = beta;

generate_frame(0.0,i_gamma,0.0,0.0,i_beta,i_bd,att_status);

}


/* boom rotates (15) with no angular acc, v (0) */


    shift = 0.0;
gamma = PI / 12.0;
time = 75.0;
frames = 1;

l_gamma =0.0;
l_beta =0.0;
i_bd[0] =0.0;
i_bd[1] =0.0;


for (i=1; i<(time*frames +1); ++i)
{

   inst_time = i / frames;
   i_gamma = gamma / (time*frames);

zzshift = (600.0 - xshift) * sin(PI/12.0 + (i_gamma * i));


beta = (s51_fin_ang_vel * sqrt(L/g) * sin(sqrt(g/L)*inst_time) +
   s51_fin_beta * cos(sqrt(g/L)*inst_time));


ang_vel = s51_fin_ang_vel * sqrt(L/g) * sqrt(g/L) * cos(sqrt(g/L)*inst_time) -
   s51_fin_beta * sqrt(g/L) * sin(sqrt(g/L)*inst_time);


tension = (W/g) * (ang_vel*ang_vel/L) +
          (W * sqrt(1.-(sin(beta)*sin(beta))));

boom_deflect[1] = tension * R * R * R * (1 - cos(90.*PI/180.)) / (3. * E * I);

boom_deflect[0] = tension * R * R * R * (1 - cos(90.*PI/360.)) / (3. * E * I);

   if (i == (time*frames))
      {
       s52_fin_beta = beta;

       s52_fin_ang_vel = ang_vel;
      }

generate_frame(0.0,i_gamma,0.0,0.0,i_beta,i_bd,att_status);

}
```

```
/* boom rotates (15) with angular acc, v (-) */

    shift = 0.0;
gamma = PI / 12.0;
time = 75.0;
frames = 1;

l_gamma =0.0;
l_beta =0.0;
i_bd[0] =0.0;
i_bd[1] =0.0;

for (i=1; i<(time*frames +1); ++i)
{
   inst_time = i / frames;
   i_gamma = gamma / (time*frames);


zzshift = (600.0 - xshift) * sin(PI/6.0 + (i_gamma * i));

beta = -1.0 * (pow(inst_time, 12)*pow(v, 7))/(3840.*R*g) +

(11.* pow(inst_time, 10)* pow(v, 7)*L/(320.*R*g*g)) -

(pow(inst_time, 8)* pow(v, 5)*(g*g*(R*R-8.)+1188.*v*v*
   L*L))/(384.*R*g*g*g) -

(pow(inst_time, 6)*pow(v, 5)*(7.*g*g*L*(8.-R*R)-
   8316.*v*v*L*L*L))/(48.*R*g*g*g*g) -

(pow(inst_time, 4)* pow(v, 3)*(g*g*g*g*(4.-R*R)+
   41580.*v*v*v*v*v*L*L*L*L+35.*v*v*g*g*L*L*(R*R-8.)))/(8.*R*g*g*g*g*g) -

(inst_time*inst_time*v*v*v)*(105.*v*v*g*g*L*L*L*(8.-R*R)+3.*g*g*g*g*L*(R*R-4.)-
   124740.*v*v*v*v*L*L*L*L*L)/(2.*R*( pow(g, 6))) -

v*(3.*v*v*g*g*g*g*L*L*(8.-R*R)+105.*v*v*v*v*g*g*L*L*L*L*(R*R-16.)+
   2.*R*R*(pow(g, 6))+249480.*(pow(v, 6))*
   (pow(L, 6)))/(2.*R*(pow(g, 7))) +

(s52_fin_ang_vel * sqrt(L/g) * sin(sqrt(g/L)*inst_time) +
   s52_fin_beta * cos(sqrt(g/L)*inst_time)) ;


ang_vel = -1.0 * ( pow(inst_time, 11)* pow(v, 7))/(320.*R*g) +

(11.* pow(inst_time, 9)* pow( v, 7)*L/(32.*R*g*g)) -

(pow( inst_time, 7)* pow( v, 5)*(g*g*(R*R-8.)+1188.*v*v*
   L*L))/(48.*R*g*g*g) -

( pow( inst_time, 5)* pow(v, 5)*(7.*g*g*L*(8.-R*R)-
   8316.*v*v*L*L*L))/(8.*R*g*g*g*g) -

(pow( inst_time, 3)* pow( v, 3)*(g*g*g*g*(4.-R*R)+
   41580.*v*v*v*v*v*L*L*L*L+35.*v*v*g*g*L*L*(R*R-8.)))/(2.*R*g*g*g*g*g) -

(inst_time*v*v*v)*(105.*v*v*g*g*L*L*L*(8.-R*R)+3.*g*g*g*g*L*(R*R-4.)-
   124740.*v*v*v*v*L*L*L*L*L)/(R*(pow(g, 6))) +

s52_fin_ang_vel * sqrt(L/g) * sqrt(g/L) * cos(sqrt(g/L)*inst_time) -
   s52_fin_beta * sqrt(g/L) * sin(sqrt(g/L)*inst_time);


tension = (W/g) * (ang_vel*ang_vel/L-v*inst_time*v*inst_time/R
          *(cos(-v*inst_time*inst_time/2) +
          sin(-v*inst_time*inst_time/2))-v*R*(sin(-v*inst_time*inst_time/2)
          -cos(-v*inst_time*inst_time))) +
          W * sqrt(1.-(sin(beta)*sin(beta)));

boom_deflect[1] = tension * R * R * R * (1 - cos(90.*PI/180.)) / (3. * E * I);

boom_deflect[0] = tension * R * R * R * (1 - cos(90.*PI/360.)) / (3. * E * I);

generate_frame(0.0,i_gamma,0.0,0.0,i_beta,i_bd,att_status);

}
    gexit();
}
```

Sample Case (genframe c)

```
/* This function generates the object frames at the specified transformation
   values using pseudo-kinematic transformations to achieve desired spatial
   orientation required */

/* Written by Shrikant Dixit */

#include <math.h>
#include <gl.h>
#include <device.h>

extern genrot( );
extern mat4x4( );
extern initmat( );
extern show_frame( );

extern int obj_polylist[6][800][100],total_obj_points[10];
extern float obj_points[6][1500][3],disp_list[6][1500][3];
extern float xshift,yshift,xxshift,zzshift;

generate_frame(shift,gamma,theta,delta,beta,boom_defl,att_status)
float shift,gamma,theta,delta,beta,boom_defl[2];
int att_status;

{
    float tempx,tempy,tempz;
    int i,j,k,objects;

    color(BLACK);
    clear( );

    xshift += shift;

    /* assign display list to normal state
    for(i=0;i<6;++i)
    {
        for(j=0;j<total_obj_points[i];++j)
        {
            disp_list[i][j][0] = obj_points[i][j][1];
            disp_list[i][j][1] = obj_points[i][j][2];
            disp_list[i][j][2] = obj_points[i][j][0];
        }
    }

    /* set objects to be manipulated */

    objects = 5;
    if(att_status==1)
        ++objects;

    /* deform the boom */

    for(j=4;j<8;++j)
        disp_list[2][j][1] += boom_defl[0];

    for(j=8;j<12;++j)
        disp_list[2][j][1] += boom_defl[1];

    /* apply boom effect to cable and object */

    yshift += boom_defl[1];
    for(i=3;i<objects;++i)
    {
        for(j=0;j<total_obj_points[i];++j)
            disp_list[i][j][1] += boom_defl[1];
    }

/*  move for beta */

    for(i=3;i<objects;++i)
    {
        for(j=0;j<total_obj_points[i];++j)
        {
            tempy = disp_list[i][j][1];
            tempz = disp_list[i][j][2];
            disp_list[i][j][1] = cos(beta) * (tempy - yshift)
                               + sin(beta) * (tempz - zzshift) + yshift;
            disp_list[i][j][2] = -1.0 *sin(beta) * (tempy - yshift)
                               + cos(beta) * (tempz - zzshift) + zzshift;
        }
    }
/*  move for delta */

    for(i=3;i<objects;++i)
    {
        for(j=0;j<total_obj_points[i];++j)
        {
            tempx = disp_list[i][j][0];
            tempy = disp_list[i][j][1];
            disp_list[i][j][0] = cos(delta) * (tempx - 600.0)
                                 + sin(delta) * (tempy - yshift) + 600;
            disp_list[i][j][1] = -1.0 * sin(delta) * (tempx - 600.0)
                                 + cos(delta) * (tempy - yshift) + yshift;
        }
    }

/*  move for theta */

    for(i=2;i<objects;++i)
    {
        for(j=0;j<total_obj_points[i];++j)
        {
            tempx = disp_list[i][j][0];
            tempy = disp_list[i][j][1];
            disp_list[i][j][0] = cos(theta) * tempx
                                 + sin(theta) * tempy;
            disp_list[i][j][1] = -1.0 * sin(theta) * tempx
                                 + cos(theta) * tempy;
        }
    }
/*  move for gamma */

    for(i=1;i<objects;++i)
    {
        for(j=0;j<total_obj_points[i];++j)
        {
            tempx = disp_list[i][j][0];
            tempz = disp_list[i][j][2];
            disp_list[i][j][0] = (cos(gamma) * (tempx - xshift))
                                 - (sin(gamma) * tempz) + xshift;
            disp_list[i][j][2] = (sin(gamma) * (tempx - xshift))
                                 + (cos(gamma) * tempz);
 /*           xxshift *= sin(gamma)
            zzshift *= cos(gamma)
   */     }
    }

/*  move for shift */

    for(i=0;i<objects;++i)
    {
        for(j=0;j<total_obj_points[i];++j)
            disp_list[i][j][0] += shift;
    }


    show_frame();
    swapbuffers();
}
```

Sample Case (showframe c)

```
/* This functions draws the specified objects */

/* written by shrikant dixit */

#include <stdio.h>
#include <gl.h>
#include <device.h>

extern float disp_list[6][1500][3];
extern int obj_polylist[6][800][100],total_obj_poly[10],total_obj_points[10],
           points_per_poly[6][800];

show_frame( )

{
    int i,j,ppbnd,ob_no;
    float parray[1000][3],x,y,z;

zbuffer(TRUE);
zclear( );

for(ob_no=1;ob_no<7;++ob_no)
{
        makeobj(ob_no);
        color(ob_no);
    for( i=0;i<total_obj_poly[ob_no - 1];i++)
    {
        ppbnd = points_per_poly[ob_no -1][i];

        for (j=0;j<ppbnd;++j)
        {
            parray[j][0] = disp_list[ob_no - 1]
                                [obj_polylist[ob_no -1][i][j] - 1] [0];
            parray[j][1] = disp_list[ob_no - 1]
                                [obj_polylist[ob_no -1][i][j] - 1] [1];
            parray[j][2] = disp_list[ob_no - 1]
                                [obj_polylist[ob_no -1][i][j] - 1] [2];
        }

        poly(ppbnd,parray);
    }
        closeobj(ob_no);
    callobj(ob_no);
}
}
```

Sample Case (initgraph c)

```
/* sample gl drawing */

/* witten by shrikant dixit */

#include <stdio.h>
#include <gl.h>
#include <device.h>

int init_graphics( )
{
    static float parray[5][3] = {0.0,0.0,0.0,
                                 10.0,0.0,0.0,
                                 10.0,10.0,0.0,
                                 0.0,10.0,0.0,
                                 0.0,0.0,0.0};
    int junk;

    /* initialize gl */

    /* set the text window) */

    keepaspect(4,3);
    /* prefposition(24,1000,18,750); */
    prefsize(1200,900);
    junk = winopen("MTMP");
    wintitle("MULTI-TASK MOTION PLANNING");
    doublebuffer( );
    gconfig( );
    qdevice(INPUTCHANGE);
    qdevice(REDRAW);
    color(BLACK);
    clear( );
    /* viewport(100,900,100,700);
    ortho(0.0,40.0,0.0,30.0,0.0,30.0); */

   /* viewport(28,996,103,697); */
    viewport(0,1200,0,900);
    perspective(650,1.33333333,0.1,2000.0);
    lookat(1000.0,300.0,1000.0,500.0,300.0,0.0,0);
    /* exit gl */

    return;
}
```

Sample Case (newint c)

```
/* This program computes the integral properties of solids */

/* Written by Taylan Dal */

#include <stdio.h>
#include <math.h>


/* function to compute integral properties */

int integprop(nt,trianglelist,density,totalvolume,totalI_xx,totalI_yy,
totalI_zz,totalI_xy,totalI_xz,totalI_yz,totalmass)

/* argument decleration */

float trianglelist[3][3][500],density;
float *totalvolume, *totalI_xx, *totalI_yy, *totalI_zz, *totalI_xy,
     *totalI_xz, *totalI_yz, *totalmass;

int nt;

{

/* variable decleration */

float volume,C_x,C_y,C_z,Ix,Iy,Iz,I_xx,I_yy,I_zz,
        I_xy,I_xz,I_yz,x[3],y[3],z[3],det,mass;

int i,j,status;

   /* error check */

   status=1;
        *totalvolume=0.0;
        *totalI_xx=0;
        *totalI_yy=0;
        *totalI_zz=0;
        *totalI_xy=0;
        *totalI_yz=0;
        *totalI_xz=0;
        *totalmass=0;

   for (i=0;i<nt;i++)                              /* number of triangles */
       {

        for (j=0;j<3;j++)                          /* vertex number */
            {

             /* get x,y,z values */

             x[j]=trianglelist[0][j][i];
             y[j]=trianglelist[1][j][i];
             z[j]=trianglelist[2][j][i];

            }

        /* find determinant of the transformation matrix */

        det=(x[0]*(y[1]*z[2]-y[2]*z[1])-x[1]*(y[0]*z[2]-y[2]*z[0])
                  +x[2]*(y[0]*z[1]-y[1]*z[0]));

        /* find volume */


        volume=det/6.;

        *totalvolume += volume;


        /* find center of mass */

        C_x=(x[0]+x[1]+x[2])/4.;

        C_y=(y[0]+y[1]+y[2])/4.;

        C_z=(z[0]+z[1]+z[2])/4.;
        /* find moments of inertia */

        Ix=(x[0]*x[0]+x[1]*x[1]+x[2]*x[2]+x[0]*x[1]+x[0]*x[2]+x[1]*x[2])
                *volume/10.;


        Iy=(y[0]*y[0]+y[1]*y[1]+y[2]*y[2]+y[0]*y[1]+y[0]*y[2]+y[1]*y[2])
                *volume/10.;


        Iz=(z[0]*z[0]+z[1]*z[1]+z[2]*z[2]+z[0]*z[1]+z[0]*z[2]+z[1]*z[2])
                *volume/10.;

        I_xx = Iy + Iz;
        I_yy = Ix + Iz;
        I_zz = Iy + Ix;

        *totalI_xx += I_xx;
        *totalI_yy += I_yy;
        *totalI_zz += I_zz;

        I_xy=(2*(x[0]*y[0]+x[1]*y[1]+x[2]*y[2])
                +(x[0]*y[1]+x[1]*y[0]+x[0]*y[2]+x[2]*y[0]+x[1]*y[2]+x[2]*y[1]))
                *volume/20.;

        *totalI_xy += I_xy;

        I_yz=(2*(z[0]*y[0]+z[1]*y[1]+z[2]*y[2])
                +(z[0]*y[1]+z[1]*y[0]+z[0]*y[2]+z[2]*y[0]+z[1]*y[2]+z[2]*y[1]))
                *volume/20.;

        *totalI_yz += I_yz;

        I_xz=(2*(x[0]*z[0]+x[1]*z[1]+x[2]*z[2])
                +(x[0]*z[1]+x[1]*z[0]+x[0]*z[2]+x[2]*z[0]+x[1]*z[2]+x[2]*z[1]))
                *volume/20.;

        *totalI_xz += I_xz;


        /* find mass */


        mass=volume*density;

        *totalmass += mass;

       }
       status=0;
       return(status);
}
```

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