A System for Automated Fixture Planning with Modular Fixtures

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Abstract

This thesis describes a system to advance the automation of the fixture planning process with modular fixture components. Algorithms consider both physical constraints of metal cutting principles and geometric constraints. These algorithms automatically generate fixture plans with a minimal number of overhead clamps or a vise. We verified the system by planning fixtures for a number of machined test parts.

In order to generate practical fixture plans, the system considers actual fixture components available in the fixture library. The system considers fixture requirements such as geometric, kinematic, and force constraints in order to automate the generation of fixture plans with little or no human assistance. Since the number of clamps in a fixture plan is often related to the cost, candidate fixture plans with a small number of clamps are first generated by placing clamps on discretized candidate clamp locations on the part. In each candidate fixture plan with known clamp locations, the algorithm checks the interference between part/fixtures/cutter paths and fixtures, and estimates the minimal clamping force to hold the part rigidly. A locating plan and a supporting plan are made considering the clamping plan and locating/supporting principles. The algorithm to generate fixture plans using a vise determines various valid candidate jaws' positions and the parallel bars' heights using extensive geometric reasoning on cutter paths, the part, and the vise geometry. The necessary clamping force is estimated in consideration of the contact area between the jaw and the part.

The system has been integrated and tested with the other intelligent modules necessary for the automation of various metal cutting processes. The system typically generates multiple fixture plans for a setup within a few CPU seconds. The result shows that the system can be incorporated into a setup planning system to quickly generate a metal cutting setup sequence.

This thesis is dedicated to
My Parents,
My Wife, Jinhee,
and to
My Sons, Daniel and Junil.

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Chapter 1
Introduction

1.1. Background

Industry has increasingly paid more attention to the automation of nearly every facet of manufacturing in order to enhance the quality of products and productivity. In addition, customers' ever-increasing demand for rapid production has forced industry to put more effort into automation than ever before. As a result, industry used computer-aided design (CAD) and computer-aided manufacturing (CAM) tools to successfully automate part design, drafting, scheduling, and other steps in various manufacturing processes.

Metal cutting is a labor-intensive manufacturing process that requires expensive machine tools and highly skilled human experts with previous hands-on experience. In metal cutting, it has been a constant goal to enhance productivity and meet the customer's demand to produce better quality parts faster than before. In recent years, there has been much success in automating various metal cutting processes. For example, computer numerically control (CNC) and direct numerical control (DNC) have increased the productivity of machine tools by programming NC codes at a distance or from a remote terminal and downloading them to machine tools. Also, NC codes have been automatically generated with an expert system resulting in substantial reduction in manual programming time [Preiss 84].

Recently, metal cutting industries have begun to experience difficulty finding highly skilled machinists because the number of apprentices is decreasing. It is likely that the situation will worsen in the future according to the trend. As a result, the need for automation of the metal cutting process has increased rapidly.

Once the dimension of raw stock is determined to create a part, a metal cutting process can be divided into two major activities; 1) setup planning and 2) machining according to setup plans. Setup planning lays out the necessary metal cutting operations to create the part from raw stock by determining the number of setups and the setup sequence. In order to fully automate a metal cutting process, both the setup planning and the actual cutting procedure must be automated. However, the complexity and many uncertainties in the metal cutting process have impeded the progress toward automation.

The setup in metal cutting specifies the orientation and position of the part on the machine bed, a set of features to be cut, a plan to cut each feature (We call this a cutting plan), and a plan to locate the part accurately relative to the cutting tool and hold the part rigidly in position (We call this a fixture plan). A cutting plan specifies the necessary cutting tools, tool paths, feed rate, and depth of cut, etc. A fixture plan

describes how the part is held on the machine table. In order to fully automate setup planning, it is necessary that the cutting plan and fixture plan be automatically generated.

There have been some research efforts to automatically generate cutting plan. For example, CUTTECH [Barkocy 84] is an user-interactive expert system that can generate cutting plans for a setup once a human expert (machinist) specifies the geometry of a feature and a preferred machine tool through a menu-driven program.

In most setups, a cutting plan can be generated by considering only the geometry of features to be created independent of a fixture plan [Barkocy 84]. Although a fixture plan could be also generated by considering only the geometry of features independent of a cutting plan, the uncertainty in estimating the necessary clamping force prevents a tool designer from generating a practical fixture plan. Thus, it is desirable for a tool designer to have information on the magnitude and direction of the cutting forces from a cutting plan to better estimate adequate clamping force to hold the part in a setup.

1.2. Automation of Fixture Planning

With a CNC machine tool's ability of measuring up to one thousand of an inch, a fixture dominantly affects the accuracy of the part. A poorly designed or assembled fixture may cause cutters to break due to chatter, and the part may have to be scrapped due to failure in holding during machining or due to inaccuracy. Thus, at present, fixture planning often requires a lot of time and careful consideration from an experienced tool designer.

A fixture plan can be made by either designing a fixture solely manufactured for specific parts or constructing a flexible fixture with modular fixture components. A well designed dedicated fixture can hold the part faster and can ensure better part accuracy than modular fixtures. However, due to the cost and time it takes to design and fabricate it, a dedicated fixture is only economically justifiable for large batch size production or when it is difficult to construct modular fixtures due to the part shape and complex cutting operations [Hoffman 87].

A modular fixturing system consists of various components such as locators, supports, clamps, modular vises, and parallel bars, etc. (see Figure 1-1). Modular fixture components can be assembled on various base plates such as sine plates and angle plates depending on the part orientation required in a setup. Modular fixturing systems provide flexibility in fixture planning because components can be used. Although the initial investment for a modular fixturing system is costly than that of a dedicated system, it is a better solution economically for a small batch size production because it is flexible and can be used repeatedly [Hoffman 87].

Recent trends in metal cutting has shown a sharp increase in small batch size production, and thus modular fixturing systems are becoming more popular due to their economy and versatility. In this thesis, we consider fixture planning with a modular fixturing system.

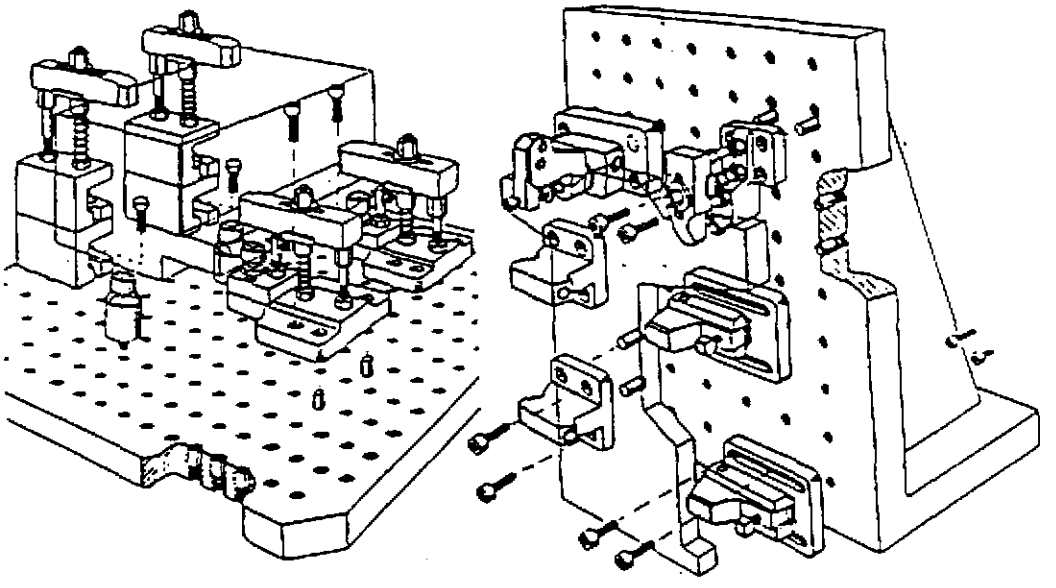


Figure 1-1: A modular fixturing system [Hoffman 87]

Currently, fixture planning with modular components relies on a human expert (tool designer). Based on his/her experience, the tool designer selects appropriate fixture elements from a modular fixturing system and determines their locations considering various fixture requirements that are typically conflicting each other. Because this procedure is done using vast human experience, it is often time consuming for experienced tool designers to generate a *good* fixture plan when the part geometry or cutting operations are complex. Thus, fixture planning has been the least automated process in metal cutting and a major bottleneck toward automated setup planning.

Various computer-aided fixture planning systems have been developed to help a tool designer generate fixture plans with modular fixture components. A typical CAD tool provides an environment for a tool designer to select the necessary fixture components from its data base in order to graphically construct a possible fixture on the graphics screen. Although a system may speed up the fixture planning process, critical decisions such as the selection of fixture components and the determination of their locations still rely on a human expert. As a result, the quality of a fixture plan depends heavily on a human expert's capability.

1.3. Effect of Fixture Plans on Cost Effective Setup Planning

Previous research related to setup planning typically has considered feature geometry without fully considering cutting plans or fixture plans [Hayes 91] [Nau 87]. This research either considers cutting sequence in a setup or assumes that a fixture plan exists for each setup. As a result, setup plans and their sequence may not be valid if a cutting plan or a fixture plan does not exist for a setup. Assembly of the fixture typically takes a much longer time compared with the time spent for other processes. Time spent for the assembly of a fixture plan ranges from several minutes for a simple setup to several hours for a complex setup [Hoffman 87]. Thus, the reduction of fixture assembly time is often critical in increasing the productivity and in optimizing part cost. The quality of a fixture plan can be measured by the time necessary for assembly if the part accuracy is ensured during machining.

A typical fixture plan consists of locators, supports, and clamps. In general, clamps are the most time consuming fixture components during fixture assembly relative to the assembly time for supports and locators. The assembly time of clamps proportionally increases with the number of clamps in a fixture plan. Thus, it is desirable to use the smallest number of clamps in a fixture plan that can exert adequate clamping force to hold the part.

In metal cutting, many parts require more than one setup due to limitations in either cutting tools or fixtures. In general, as the number of setups increases, the cost and time to assemble the fixtures and machine the part also increases, and the part's accuracy tends to deteriorate. Thus, it is desirable to generate the minimum number of setups.

The number of setups and their sequence may be determined only by considering the geometry and orientation of the features and/or the machine tools' cutting capabilities without considering detailed fixture plans [Hayes 91]. If a fixture plan could be generated for each setup, setup plans and their sequence would be successfully used for actual machining process. However, when a fixture plan is not available for a setup due to limited fixturing capabilities or other reasons, the setup should be divided into multiple sub-setups.

Fixture plans with a small number of clamps are often crucial to achieve the minimum number of setups and reduce the overall fixture assembly time in various setups. The number of clamps in a fixture plan is determined by considering cutting forces and a clamp's maximum clamping force. However, it is not easy to accurately estimate the clamping force because the magnitude and direction of a cutting force is difficult to measure. In order to ensure the rigidity in part/fixture assembly during machining, a tool designer often generates conservative fixture plans that require more clamps with a larger clamping force than actually required. Clamp locations are spread apart to maximize the ability to offset moments created by cutting tools from various directions. This would not only increase the time to assemble clamping components, but also would increase the danger of part deflection in a thin part due to a larger clamping force. Moreover, the fixture plan may not be successful due to interference among clamps. This will increase the number of setups and result in a much longer setup time.

By estimating the necessary clamping force more accurately and placing clamps at proper locations, it is often possible to use smaller number of clamps to hold the part than the number of clamps in a fixture plan generated by a human expert with a conservative estimation.

1.4. Objective

The objective of this thesis is to develop a system that advances the automation of generating cost-effective fixture plans with modular fixtures for a given metal cutting setup.

Fixture planning will consider the following:

- Automated selection of fixture components from a data base
- Automated determination of fixture components' locations
- Automated estimation of the clamping force
- Automated generation of fixture plans with a minimum number of clamps

1.5. Domain

In a modular fixturing system, various clamping components exist: overhead clamps, side clamps, and a movable vise jaw. Overhead clamps apply their clamping force perpendicular to a fixture base plate, and side clamps apply their clamping force parallel to a fixture base plate. A movable vise jaw can be considered as a side clamp since it applies clamping force parallel to a fixture base plate.

Depending on what clamping components are used, a fixture plan may vary significantly from one to another due to the different constraints. The most popular fixture plans in practice are made with either overhead clamps or a vise. A vise is usually the most cost-effective workholding tool for a rectangular parts due to its fast and rigid holding capability, and thus it has been widely used in practice. However, little research has been conducted to automate the fixture planning process with a vise.

In this thesis, we consider automation of fixture planning with overhead clamps or a vise.

1.6. Summary

This thesis describes a system that automatically generates practical fixture plans with modular fixture components. The system consists of two algorithms developed to automate fixture planning with overhead clamps and a vise, respectively. The system considers the geometry and limitations of each fixture component in the fixture library in order to select necessary components and determine their location and the clamping force.

Fixture components' dimensions and limitations are parameterized and stored in a data base. A fixture component's geometry can be dynamically constructed from its parameters and represented around the part when its position and orientation are specified in the part coordinate.

New and existing analytical tools are developed and used to generate multiple candidate fixture plans and check their validity against various fixture requirements. For faster interference checking, simple polyhedra with a small number of faces have been used to model fixture components and swept volumes of cutter paths, and fast interference checking methods have been employed to avoid a computationally intensive 3D algorithm. Screw theory has been applied to check part rotation due to clamping during the assembly. To compute the least clamping force to maintain a part's force/moment equilibrium, problems are treated as a problem of minimizing clamping force, and a linear programming method is used as a mathematical tool to solve this problem.

An algorithm for fixture planning with overhead clamps is developed to generate fixture plans with a minimal number of clamps to reduce assembly time and the least clamping force in order to minimize the problem of part deflection. For a selected clamp type, the algorithm identifies clampable locations by discretizing the edges of the clampable part surfaces into points and then checks each discretized point's feasibility as a candidate clamp location against fixturing constraints. Using these candidate clamp locations, the algorithm exhaustively generates all valid clamping plans with the minimum number of clamps. For each clamp plan, the types and positions of locators to accurately locate the part are determined according to the 3-2-1 locating rule, and supports are placed under clamps when the part needs to be lifted from the fixture base.

For fixture planning with a vise, an algorithm is developed to identify every possible area for jaw contact on the part. Then, the algorithm generates a fixture plan by determining the location of both jaws on each accessible area. A 2D geometric reasoning scheme has been developed to identify the area for the jaw contact. In each plan, the minimum clamping force to hold the part is estimated to reduce the chance of part deflection due to clamping force.

When there are multiple fixture plans with the same number of clamps or the same type of vise, a fixture plan with a smaller clamping force is typically more favored than one with a greater clamping force because it has less chance of part deflection. In each algorithm, fixture plans are rated and ordered according to their magnitude of clamping force. Thus a human expert can select the most favorable fixture plan with either clamps and/or a vise while considering the problem of part deflection and other constraints.

Due to the capability of geometric reasoning in the algorithms, the system is applicable to any generic part shape. Also, the system is designed to accommodate various modular fixturing systems. A fixture data base for a modular fixturing system can be quickly established and easily modified.

The system requires the assistance of human expert to evaluate a fixture plan for the possibility of deformation of part due to clamping force when clamping or cutting force is applied to ill supported areas of a thin part. A human expert may visually identify any unacceptable part deflection due to clamping or cutting force by inspecting a simulated part/fixture assembly displayed on a graphics screen. When there is part deflection in a fixture plan with clamps, the human expert may add extra supports or use a subplate to prevent unacceptable part deflection. In order to automatically detect part deflection, an accurate force model is required and an expert system using a mathematical analysis such as a finite element method (FEM) needs to be developed in the future.

1.7. Contributions

Major contributions of this thesis can be summarized as follows:

1. Development of an algorithm for automated fixture planning with overhead clamps
2. Development of an algorithm for automated fixture planning with a vise
3. Development of 2D force analysis to estimate clamping force when clamp locations and the direction and magnitude of the cutting forces are known.
4. Generation of practical fixture plans
5. Complete interference checking between fixture components and part/fixture components/cutter paths
6. Application of screw theory to check part rotation due to the clamping location
7. Generation of fixture plans with a minimum number of clamps and minimum clamping force
8. Extendibility of algorithms to various modular fixture systems

1.8. Organization of Thesis

This thesis is organized as follows.

In Chapter 2, an overview of previous work on automated fixture planning and related research has been given.

In Chapter 3, various analytical tools used to automate the fixturing process are introduced. Mathematical tools used to check interference between polyhedra, to check part rotation due to clamping during assembly, and to compute the least clamping force with the specified clamp location are described.

In Chapter 4, a system to automatically generate efficient fixture plans with either clamps or a vise in a modular fixturing system is presented. Assumptions and inputs required for the system are also described.

In Chapter 5, an algorithm to generate fixture plans with clamps is presented and the reasoning and analytical tools used in the various steps are described in detail.

In Chapter 6, an algorithm to generate fixture plans with a vise is presented and the reasoning and procedures used in the various steps are described in detail.

In Chapter 7, the implementation of the system is described and several examples of fixture plans with different part geometries and cutting operations are used to demonstrate the system's capability. Also, complete setup sequences generated with the system for two sample parts are demonstrated. A setup sequence for a test part similar to one of the sample parts is generated and machined.

In Chapter 8, we conclude this thesis and describe the future research that needs to be pursued to further automate the fixture planning process.

Chapter 2
Literature review

Two major approaches to the automation of fixture planning with modular fixtures are : 1) knowledge based expert systems, and 2) generative expert systems.

2.1. Knowledge Based Fixture Planning Systems

As modular fixturing is gaining in popularity, various computer-aided fixture planners (CAFP) have been developed to assist a human expert to quickly generate fixture plans.

Knowledge based expert systems take advantage of accumulated rules or the knowledge of human experts. Human expert can select the necessary fixture components and determine their configurations by interacting with a CAD system. Markus [Markus 84] has developed an expert system which determines the necessary erector sets to raise the clamps and the part to the desired height once the clamp location is determined. Expert systems using various AI techniques have been proposed to provide guidelines for fixture generation [Ferreria 85] [Nee 87] [Nnaji 88]. These systems are typically complex, and their performances are highly dependent on the experience of users.

Recently, a group technology based CAD system for modular fixture assembly has been developed to retrieve fixture designs that are already made for similar parts [Zhu 92]. A typical CAFP has a knowledge base for fixture components [Miller 85].

Most expert systems help a human expert accelerate the search for the necessary components rather than replacing the human expert. Critical decisions such as determining the number of clamps and their locations rely on a human expert.

With a CAFP, a human expert can generate a fixture plan on a graphics terminal faster than by hand. However, he/she must select both the fixture components from a data base and their positions on and around the part. In order to automate the fixture planning process, fixture components should be selected and their locations should be determined without help from a human expert while the fixture plan satisfies fixture requirements.

2.2. Generative Fixture Planning Systems

A generative fixture planning approach does not rely on accumulated knowledge or rules but rather automatically generates plans by identifying fixture component types and their locations based on various analytical methods and fixturing principles.

Early research on the automated fixture planning with a generative approach used kinematic restraint of the part as the primary condition to generate locations of the fixture components. That is, if a set of point contacts on the part geometry can completely restrain the part's motion and satisfy the fixturing principles on locating, supporting, and clamping, the contact points can be used for locations for actual fixture components.

Mani [Mani 88] has proposed a system based on Reuleaux's study on planar kinematic restraints [Reuleaux 76] that generates 2D fixture plans that restrain the part's motion in the plane with a number of point contacts. Once a set of point contacts are generated, locating points and clamping points are determined based on fixturing principles and heuristics. These points represent the location of modular components. The actual selection of the components and the necessary clamping forces are to be determined by a tool designer. Mani's approach is limited to generating fixture plans with side clamps because clamping forces are allowed only in the plane. Figure 2-1 shows an exemplary plan generated by his system.

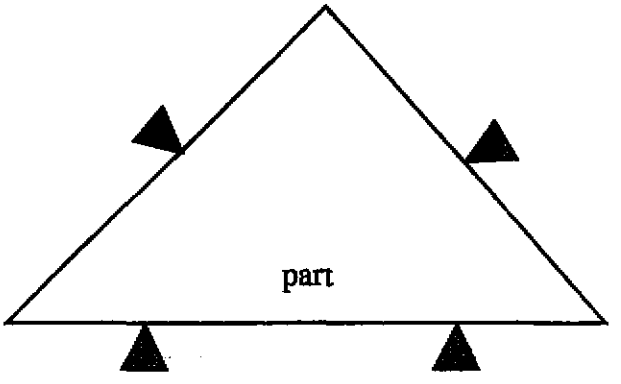


Figure 2-1: A fixture plan generated by Mani [Mani 88]

Chou [Chou 88] has developed a system that generates 3D fixture plans by restraining the part's motion in space. The problem of restraining the part is decomposed into two sub problems; restraining 1) the x-y translation and the z rotation of the part and 2) the z translation and the x-y rotation. According to his method, it seems that 2 or 3 points for clamping are used to restrain the part along with 3 point contacts for the locators and 4 points for the supports. Both overhead clamps and side clamps are required in each fixture plan. Figure 2-2 shows two sample fixture plans generated by his system. Four small disks placed under the part represent contact points for supports such as rest buttons. The three small cylinders on the part sides represent contact points for the locators. The three small cones represent contact points for either overhead or side clamps.

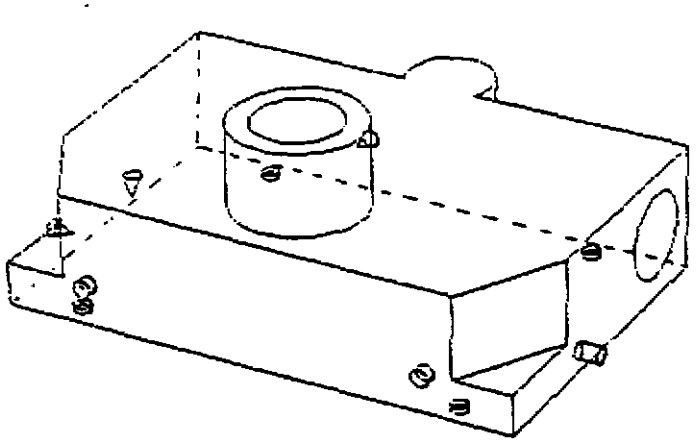


Figure 2-2: A fixture plan generated by Chou [Chou 88]

Sakurai [Sakurai 90] has developed a system that generates fixture plans with either overhead or side clamps in a given setup. His system generates more practical fixture plans than the previous approach because it considers cutter paths in determining locations of fixture components and computes the necessary clamping forces. Since the number of clamps is determined heuristically without considering cutting force, a tool engineer needs to be involved in the design loop to check the validity of a clamping plan when it requires more clamps than estimated in reality. Figure 2-3 shows two fixture plans with overhead clamps and side clamps generated by his system. Inverted L-shape polyhedra represent overhead clamps. Small cylinders placed on the base plate represent locators and small blocks represent side clamps. Note that side clamps are placed against locators and supports are placed under each overhead clamp.

The above mentioned systems do not fully consider all of the fixture requirements and as a result requires a human expert in the decision loop to generate a good fixture plan. In summary, there are several areas to be considered in the automated fixture planning with a generative approach.

1. Actual fixture components and their limitations should be considered to generate practical fixture plans.
2. Selection of fixture components should be automated to further reduce human intervention and speed up the process.
3. The number of clamps should be determined in consideration of cutting forces.
4. Each fixture requirement should be considered in determining locations of fixture components.
5. The system should automatically generate fixture plans that can be achieved in practice with little or no human intervention in a design loop.

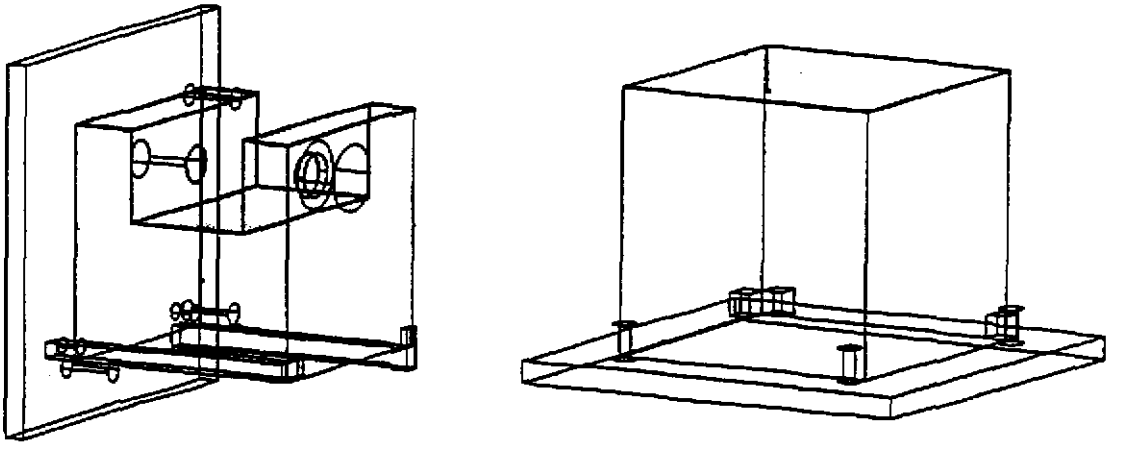


Figure 2-3: A fixture plan generated by Sakurai [Sakurai 90]

6. Automation of fixture planning process with a vise should be explored.
7. If there exist more than one fixture plan, fixture plans should be rated according to some criteria so that a human expert can select the best fixture plan.

This thesis proposes new methods to include the 7 areas just mentioned so that practical fixture plans can be generated with little or no human expert assistance.

2.2.1. Research Related to Fixture Planning

There has been a great deal of research related to automated fixture planning. Here, we only mention some of the important research. Ingrand [Ingrand 84] and Ghandi [Grippo 87] proposed methodologies for automated fixture planning. Englert [Englert 87] has discussed the trade-off relationships between force, deformation, and part accuracy that a human expert or expert system should consider in order to generate a good fixture design. Asada [Asada 85] has analyzed the position of fixture components placed to locate the workpiece, and he has analyzed kinematically the degree of accessibility using screw theory.

Standard finite element method (FEM) software has been applied to measure part deflection when the part is held by modular fixtures under known cutting and clamping forces [Lee 86]. Menassa [Menassa 88] used FEM to calculate part deflection in a fixture plan and has determined the optimal location of supports by minimizing an objective function. However, FEM is rarely used in fixture planning because its reliability depends on the model and it is computationally very expensive.

Theoretically, grasp planning and fixture planning shares the same force and kinematic constraints. First, contacts should be placed to restrain the object's motion regardless of contact forces. Second, the contact force should maintain the object's force and moment equilibrium with or without the influence of external forces. In most grasp planning research, deformation in an object is ignored by assuming rigid objects and fingers. Also, accuracy in location is not as important as in fixturing. Some grasp planning research can be found in [Laugier 81] [Wolter 82] [Barber 86] [Ahmad 87].

2.2.2. Research on Setup Planning

Some of the recent systems related to automated setup planning are GARI [Descotte 81], TIPPS [Chang 83], SIPPS [Nau 87]. These are basically rule-based systems with AI techniques incorporated. Typically, the part is described by a set of features (feature-based model). Most setup planning systems generate a plan for one feature at a time without considering the interaction between other features. However, machining features are often inter-dependent, and an operation for a feature may need to be determined considering other features. MACHINIST [Hayes 91] has considered interactions between features in generating plans and a setup sequence. Her rules are mainly extracted from observing a few experienced human process planners' thought processes during the generation of process plans for various parts.

2.2.3. Research on Cutting Planning

The major difficulty with the current setup planning systems is that they rarely consider cutting and fixture plans. As a result, a candidate setup sequence becomes invalid when any setup does not have a valid cutter paths plan or a fixture plan. In order to generate a practical setup sequence, it is necessary for a setup planner (or an expert system) to interact with an NC programmer and a tool designer.

To generate a cutting plan for a feature, an NC programmer should perform geometric reasoning to select a tool, the number of paths, feed rate and depth of cut. While it is desirable to minimize the machining time, he should also ensure the specified accuracy of the feature. The cutting plan (or operation plan) and the NC code generation are more automated than other processes such as feature recognition. Based on AI techniques, Preiss [Preiss 84] has developed a program to automatically generate minimum time paths and write NC codes for complex features to be machined by milling machines. CUTTECH [Barkocy 84] is a user interactive program that helps a human expert quickly select the necessary machine and tool. The input for CUTTECH is information on the part material, geometry of a feature and the necessary operation. CUTTECH identifies available machines and cutters and generates the number of paths along with the depth of cut, feed rate, cutting time, etc. using cut sequencing rules and machinability data obtained from experienced machinists. Typically, a human expert prefers tools and cutting plans that require the minimum cutting time. CUTTECH is limited to some standard operations such as face milling, profile milling, slot milling, and pocket milling. Since CUTTECH generates cutting plans without considering the part geometry such as thin wall, excessive vibration or part deflection may occur. Su [Su 91] has developed a system to automatically check if a set of features in a setup can be machinable on a three-axes milling machine. Because the system does not consider interference between the swept volumes of cutter paths and the part geometry, it may result in erroneous results.

In order to further automate fixture planning process, human experts' knowledge need to be replaced by more precise analytical methods. In chapter 3, we will describe various analytical methods that can be used to automatically determine fixture components' locations and estimate the necessary clamping force.

Chapter 3
Necessary Analyses in Fixture Planning

3.1. Introduction

This chapter identifies and describes various analytical tools that are required to check necessary fixture requirements in each candidate fixture plan.

3.1.1. Requirements for Fixture Planning

Fixture planning with either clamps or a vise consists of locating, supporting, and clamping a part with various fixture components. The following are the requirements that a fixture plan with modular fixtures should satisfy.

1. There should be no interference between fixture components and cutter paths.
2. There should be no interference between fixture components and part geometry.
3. There should be no interference between fixture components.
4. A workpiece should be held rigidly during machining.
5. A fixture plan should ensure accurate position of the workpiece with respect to the machine coordinate system.
6. A fixture plan should prevent unacceptable deflection or deformation of the workpiece due to cutting and clamping force.
7. No active fixture component should cause the part to move after the part is located.
8. A fixture plan needs to be inexpensive and fast to assemble.

Most fixture requirements can be checked by analytical tools to 1) check interference between various objects in a fixture plan, 2) check part rotation due to clamping, 3) compute necessary clamping force to hold the part rigidly, and 4) check part deflection due to clamping or cutting force. While a fixture plan should satisfy every requirement, it may be difficult and time-consuming for a tool designer to perform accurate analysis without fast and reliable analytical tools.

Section 2 describes an existing method for interference checking between solid objects. Also, a few simple schemes to speed up the computation are suggested. Section 3 describes a mathematical tool that can check any part movement due to clamping during a fixture assembly. Section 4 introduces a mathematical tool used to compute the minimal clamping force while a part is held rigidly under various cutting forces. Section 5 discusses the problem of part deflection and describes schemes that a human expert uses to prevent deflection. In section 6, a summary of this chapter is given.

3.2. Interference Checking

The location of every fixture component in a fixture plan should be determined so that they do not interfere with part geometry, cutter paths, and other fixture components. Currently, when determining the location of a fixture component, a tool designer relies on visual inspection to detect any interference. Since swept volumes of cutter paths are not explicitly displayed on a typical CAD-based fixture planning system, the visual inspection of the tool designer is imprecise in nature; he/she tends to determine the location of fixture components further away from any cutter paths than necessary in order to avoid any interference with cutter paths. A precise analytic tool for interference checking would not only speed up the process, but also help determine locations of fixture components without being too conservative even under complex cutting operations.

Part geometry and fixture components' geometry can be explicitly stored in a database and displayed on a graphics terminal. The swept volume of a cutter path can be constructed in the space as a polyhedral object using the cutter's diameter and the cutter path specified in the part coordinates. The details used to construct the swept volumes will be discussed in Chapter 4.

Although algorithms exist which detect interference between two objects in space, these algorithms are computationally intensive. Thus, the possibility of interference needs to be checked first by simpler schemes to speed up the analysis. One simple scheme is to check interference by comparing the minimal and maximal x, y, and z coordinates of two objects described with respect to an arbitrary Cartesian coordinate system. Let x^A_{min}, y^A_{min}, z^A_{min}, x^A_{max}, y^A_{max}, and z^A_{max} be the minimal and maximal x, y, z coordinates of an object A. Also, let x^B_{min}, y^B_{min}, z^B_{min}, x^B_{max}, y^B_{max} be the minimal and maximal x, y, z coordinates of an object B. Then, if any of the following sufficient conditions are satisfied, there is no interference between objects A and B:

- when $x^A_{min} > x^B_{max}$, or
- when $y^A_{min} > y^B_{max}$, or
- when $z^A_{min} > z^B_{max}$, or
- when $x^A_{max} < x^B_{min}$, or
- when $y^A_{max} < y^B_{min}$, or
- when $z^A_{max} < z^B_{min}$.

Figure 3-1 shows three objects in the Cartesian coordinate system (For brevity, only x and y coordinates are shown in 2D). While the coordinate comparison recognizes that objects (A and B) and (A and C) do not interfere at all, it detects the possibility of interference between objects B and C. Thus, an intersection checking algorithm should be used to refine the answer at this point.

Another simple scheme to check the possibility of interference between two objects is to bound each object by a sphere or a cylinder and check the sum of two radii and the distance between sphere centers (Figure 3-2) [Kim 85].

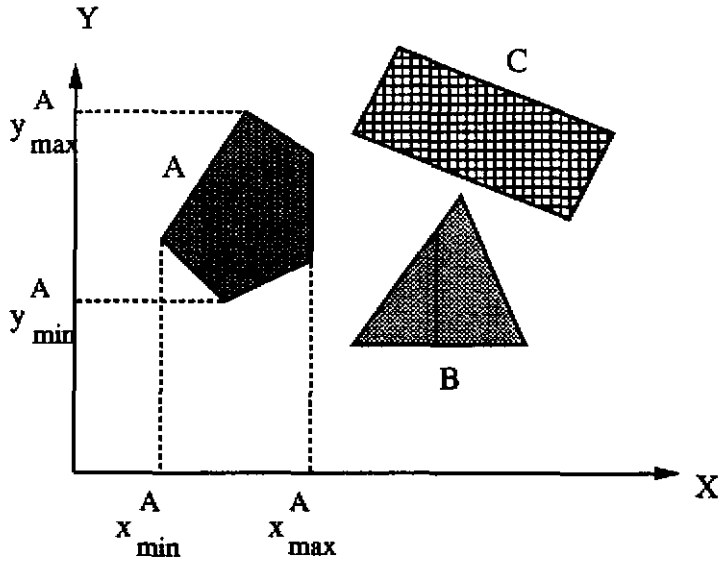


Figure 3-1: Checking for interference possibility between two objects with their minimal and maximal coordinates

Let x_1, y_1, z_1 and x_2, y_2, z_2 be the coordinates of two vertices that are separated by the longest distance in an object. Then the radius of a bounding sphere, R and the center coordinate (x_c, y_c, z_c) can be found as follows:

- $R = \sqrt{(x_1 - x_2)^2 + (y_1 - y_2)^2 + (z_1 - z_2)^2}$
- $x_c = 0.5\,(x_1 + x_2)$, $y_c = 0.5\,(y_1 + y_2)$, $z_c = 0.5\,(z_1 + z_2)$

When two objects are bounded by spheres, let R be the radius of the larger bounding sphere and r be the radius of the smaller bounding sphere. Let L be the distance between the centers of bounding spheres. If L > R + r, the two objects will not interfere. Otherwise, the possibility of interference exists, and a detailed interference checking algorithm should be applied.

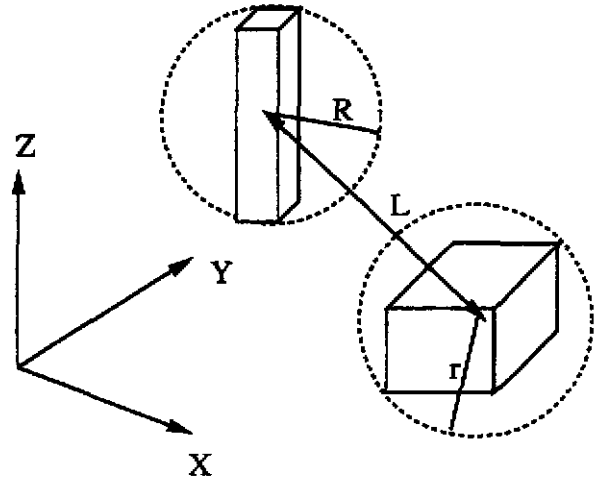


Figure 3-2: *Bounding spheres and possibility of interference*

Depending on objects' shape, one scheme may be more efficient than the other. If a simple interference checking scheme recognizes the possibility of interference, a computationally intensive algorithm needs to be used to refine the answer [Gursoz 91].

When the face of one object interferes with the face of another object, two objects are in interference. Also, if one object is completely within the other object, they are in interference. Interference checking in fixture planning can be performed between objects or between the faces of an object depending on the circumstances in order to minimize the computation time.

The computation time for an interference checking algorithm increases with the number of faces on the two objects, and it can take a long time if objects are represented by many faces. In order to speed up the interference checking, a few schemes can be used in fixture planning: 1) simplification of object geometry with a smaller number of faces, 2) consideration of only relevant faces, 3) use of a fast scheme to detect interference possibility, and 4) use of a 2D interference checking scheme.

1) Simplification of object geometry

When precise interference checking between objects is not critical in fixture planning, it is possible to speed up the computation by simplifying the object's geometry. Geometry of fixture components can be approximated by simple polyhedra with a small number of faces. For example, a cylinder type object will have many facets in boundary representation to accurately represent its side surface. By simplifying the cylinder into a rectangular block, the interference checking can be done quickly. Details on how each fixture component is simplified can be found in Chapter 4. When some clearance is needed between fixture components for easy fixture assembly and safety from the cutter paths, the geometry of fixture components should be enlarged by adding the necessary clearance.

2) Consideration of relevant faces of objects

Although an object may have many faces, only a few faces must be considered for interference checking. For example, when interference checking is required between a clamp and the part, any faces within the holes in the part can be ignored if a clamp is not placed in a hole. Even if a clamp is placed in a hole, faces within the rest of the holes can be ignored. Other pruning methods are discussed in Chapter 5; the interference checking algorithm is applied between fixture components and the part.

3) Use of a fast detection scheme to detect interference possibility

The possibility of interference between faces can be checked by comparing the maximal and minimal coordinates of both faces in the same way as it is used to check the possibility of interference between objects.

4) Use of 2D interference checking scheme

When a polyhedral object is projected onto a plane, it can be represented as a polygon. When two objects

are projected onto the same plane, interference checking can be done in 2D between 2 polygons instead of checking interference between all of the faces of the two objects. For example, the number of iterations is reduced from 36 (maximum number of iterations if each object has 6 faces) to 1. Once again, coordinate comparison of two polygons can be used to detect the possibility of interference.

This scheme is good for fast interference checking between fixture components in a fixture plan with overhead clamps, because a simplified fixture geometry becomes a rectangle when projected onto a base plate. This scheme can also be applied to interference checking between fixture components and swept volumes of cutter paths. When the swept volume is oriented co-planar with the base plate, a projection of the swept volume onto the plate is adequate to detect the possibility of interference against any fixture components.

Once fast checking schemes recognize the possibility of intersection between objects, a rigorous interference checking algorithm can be applied [Gursoz 91].

3.3. Checking part rotation due to clamping

During fixture assembly, locating and supporting components are placed ahead of any clamping components. Any clamping components should not cause the part to move during assembly in order to maintain the accurate location of the part achieved by locating and supporting components. Figure 3-3 shows examples where a clamp or vise jaw can cause the part to move during assembly.

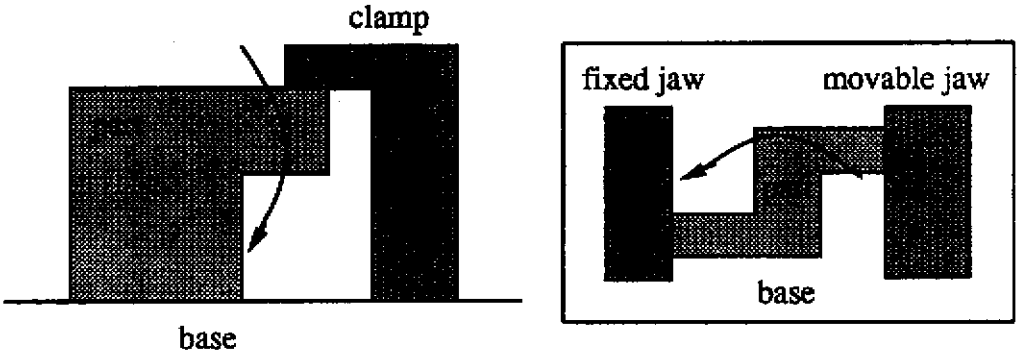


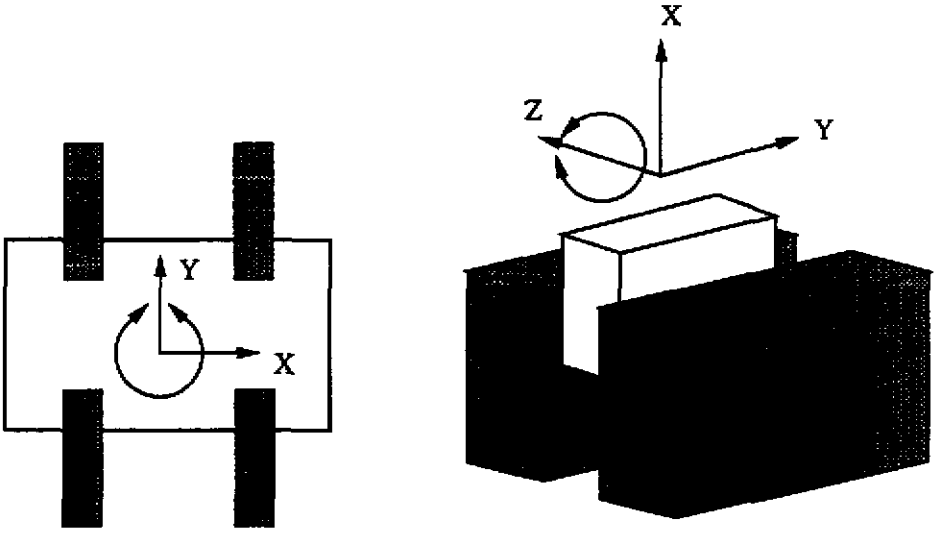
Figure 3-3: Part rotation due to a clamp or a movable jaw

In a fixture plan with overhead clamps, each clamp should be placed on the part so as not to cause it to move after the part is located and supported, regardless of clamping order. In a fixture plan with a vise, a part is located and supported by a fixed jaw and either parallel bars or a base plate. A movable jaw should not cause the part to move during assembly.

The extended screw theory developed by Ohwovoriole [Ohwovoriole 80] has been used to check part deflection due to clamping in a fixture plan. Appendix A provides a review of screw theory and how the problem formulated using his screw theory can be solved.

3.3.1. Application of Screw Theory

Screw theory can be applied to check part rotation due to active fixture components after the part is located and supported by passive fixture components. Here, we have only considered fixture plans with overhead clamps and fixture plans with a vise. While fixture plans with overhead clamps or a vise kinematically allow translation onto the plane X-Y and rotation about the Z axis, these motions are restrained by friction between fixture components and the part (Figure 3-4). Also, the configuration of fixture components in fixture plans with overhead clamps or a vise always restrains translation along the Z axis. Thus, it is only necessary to check whether a clamp or a vise can rotate the part about the X or Y axis. When a part is subject to a set of external forces (wrenches), a possible motion can be represented by a screw $t=(t_1,t_2,t_3;t_4,t_5,t_6)$ where t_1, t_2, and t_3 represents rotational motion about the X, Y and Z axis respectively and t_4, t_5, and t_6 represents translational motion along the X, Y and Z axis respectively. For an active fixture component not to rotate the part, components t_1 and t_2 in t should have only trivial solutions, since non-trivial values in any component of a twist represent the existence of motion caused by a set of wrenches.



A fixture plan with clamps

A fixture plan with a vise

Figure 3-4: Unrestrained motions in fixture plans with overhead clamps or a vise

A fixture plan with overhead clamps

When a part is supported by a base plate or a subplate, each vertex of reference faces touching a base plate or a subplate can be described by a wrench (see Figure 3-5). When a part is supported by a few supports, each support can be described by a wrench. In addition, a candidate clamp location can also be described by a wrench.

From results of screw theory, geometric reasoning can be used to detect part rotation due to clamping. The part will rotate if the projection of the clamp location to the base plate lies outside of a convex polygon

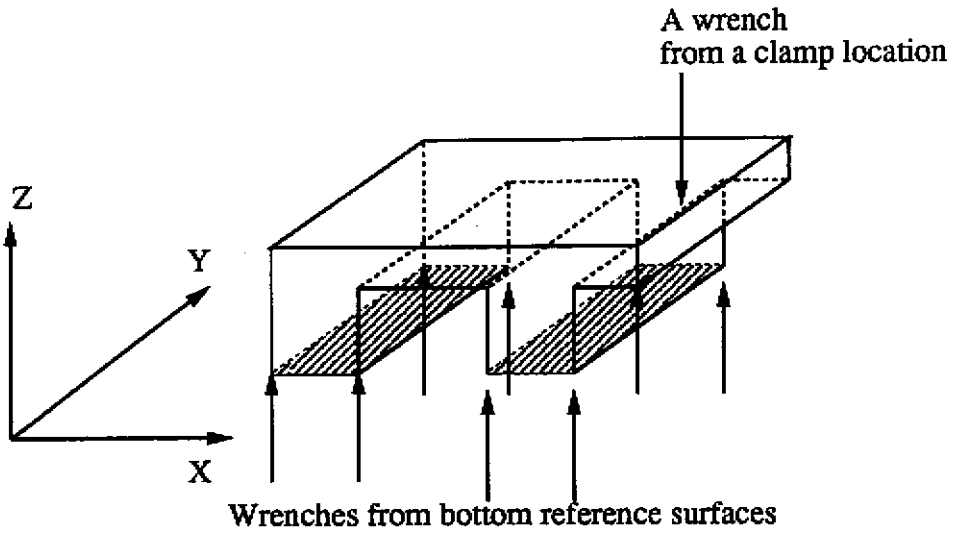


Figure 3-5: A model to check part rotation due to clamping

which bounds the contact area between the resting reference surface of the part and the supporting component (either supports or a base plate). A part in Figure 3-6 is rotated due to clamping force when it is raised from a base plate by the 3 supports since the projected clamping location is outside of the bounding polygon formed by 3 supports. Thus, in order to prevent part rotation due to clamping, supports should be placed so that the projected clamp location can be inside of the bounding polygon. When the base plate supports the part, the projected clamp location should be inside of the bounding polygon of the contact area(s) between the part and the base plate. This clamp location will not cause the part to rotate.

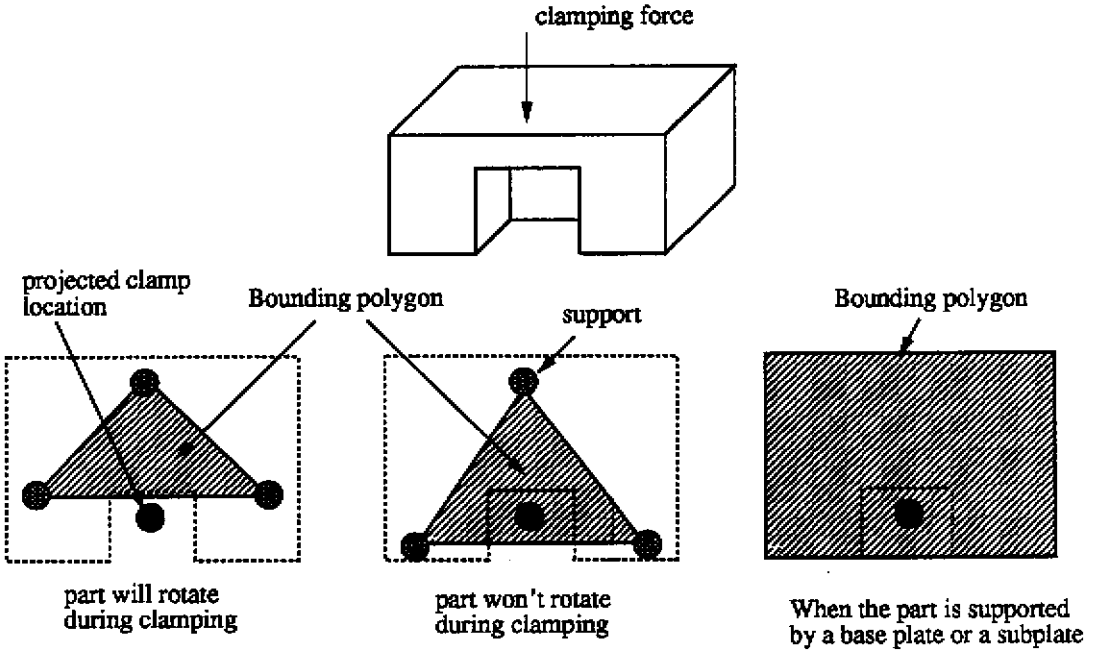


Figure 3-6: Geometric checking of a part rotation due to clamp location

A fixture plan with a vise

Vise jaws should be placed against the part, face to face. Once both jaws are placed against the part, the contact area between each jaw and the part can be identified as a bounding convex polygon. Each vertex of a polygon can be represented by a wrench. Since both polygons lie on parallel planes, all wrenches describing each polygon are perpendicular to the planes. Screw theory can be used to detect any part motion during clamping.

Geometric reasoning can be used to determine if the part would rotate due to the location of a movable jaw. The part will move during contact by a movable jaw if two polygons are not overlapped at all when they are projected onto a plane parallel to both.

3.4. Computation of clamping force

This section describes a method to estimate necessary clamping force when a fixture plan is generated with overhead clamps or a vise. Estimation of clamping force is the most critical process because it affects the quality of a fixture plan. The inadequate clamping force will scrap the part by not holding the part rigidly during machining. Applying a larger clamping force than necessary may deflect or deform the part. Thus, it is necessary to estimate the minimum clamping force. In order to estimate necessary clamping force, cutting force should first be estimated accurately. However, the accurate estimation of cutting force is difficult because it depends on cutting parameters such as the depth of cut and feed rate, etc, as well as tool wears which is hard to quantify. Experienced tool designers can make a reasonable estimation of the magnitude of cutting force.

As discussed earlier, in fixture plans with overhead clamps or a vise, planar motions such as translation on a plane and rotation about an axis perpendicular to the plane need to be restrained by friction force. Since the friction coefficient between the part and fixture components is typically small, a large clamping force is required to maintain a part's force and moment equilibrium during machining, when the motion due to the cutting force must be resisted mainly by friction force.

When a cutting force is directed out of the plane, the necessary clamping force is much smaller since the part's equilibrium does not depend on friction force. Once the magnitude and direction of the cutting force are estimated, the clamping force's magnitude can be estimated with formulas found in a machining handbook.

3.4.1. Estimation of Cutting Force

Since the magnitude of the clamping force is directly affected by the magnitude and direction of cutting force, it is important to estimate the magnitude and direction of every cutting force applied to the part as precisely as possible.

Here, only the estimation of the magnitude and the direction of drilling and milling operations are considered. In a drilling operation, the direction of thrust is equal to the direction of drill feed. Reasonable estimates of torque and thrust of sharp twist drills of various sizes and designs can be made from the following formulas [Handbook 88]:

For torque:

$$M = Kf^{0.8}d^{1.8}A$$

For thrust:

$$T = 2Kf^{0.8}d^{1.8}B + Kd^{2}E$$

where

M = torque, in-lbf
T = thrust force, lb
K = work-material constant
f = drill feed, inch per revolution(ipr)
d = drill diameter, in.
A, B, E = drill design constants

Various constants can be found in the same machining handbook according to the part material and drill cutters. For example, K is 24,000 for steel with 200 Bhn (Brinnell Hardness) and 7000 for most aluminum alloys. Drill design constants, A, B, and E are based upon the ratio c/d, where c is the chisel edge length. For drills of standard design, c/d=0.18 and A, B, and E are found to be 1.085, 1.355, and 0.03 from the table in a machine handbook [Handbook 88]. If the diameter of the drill is 1 inch and the drill feed is 0.003 ipr, when drilling a hole in steel, the torque and thrust force would be 260 in-lbf and 1370 lb, respectively. With the same diameter and feed on aluminum alloy material, the torque and thrust force would be 76 in-lbf and 400 lb, respectively. In practice, an extra 30-50% should be added to the forse estimate to allow for dulling.

In a milling operation, a cutting force can have three components: a tangential, radial, and axial cutting force (see Figure 3-7). The magnitude and direction of the overall cutting force should be obtained by the vector summation of the tangential and radial cutting forces at every cutter tooth. The direction of a tangential and radial force changes continuously at each tooth as the cutter revolves. Thus, it is not possible to estimate the magnitude of cutting force accurately and the direction cannot be expressed as a single direction.

The magnitude of tangential cutting force can be estimated from the following formula [Handbook 88]:

$$F_t = \frac{126{,}000\,HP}{D\,rpm} \tag{3.1}$$

where

F_t = tangential force, lb
HP = approximate horsepower required at the cutter
D = cutter diameter, in.
rpm = rotational speed of the cutter

Several methods have been developed for calculating the power required at the machine spindle for milling. A widely used formula is as follows [Handbook 88] [Sakurai 90]:

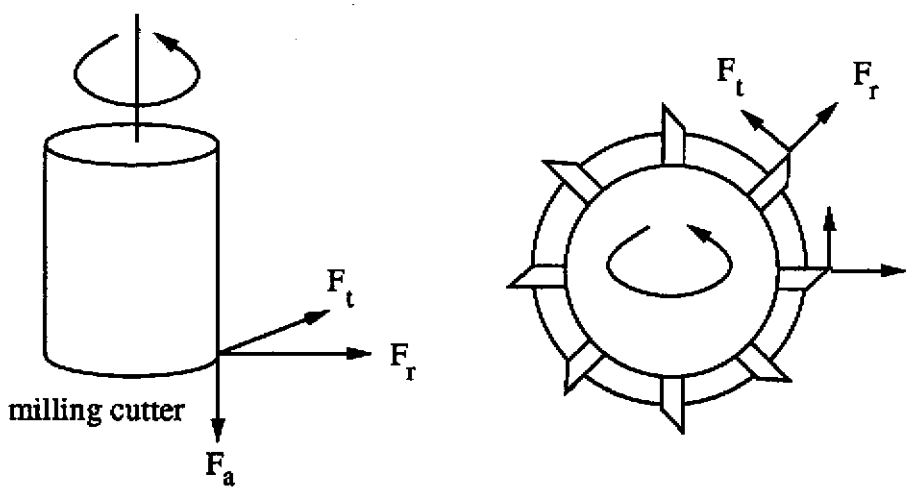


Figure 3-7: 3 force components at a tooth of a milling cutter [Smith 89]

$$HP = K s N [0.00549 (1000 A)^r] \tag{3.2}$$

where

K = a machinability factor for milling different materials
s = peripheral speed of cutter, surface feet per minute(sfpm)
N = number of cutter teeth in contact with the workpiece
A = cross-sectional area of workpiece material removed by one cutter tooth, $in.^2$
r = a machining exponent for different workpiece materials

Also,

$$s = \frac{\pi D rpm}{12} \tag{3.3}$$

$$A = fD \tag{3.4}$$

where f = feed per tooth, in.

If we substitute equations (3.2), (3.3), (3.4) into equation (3.1), F_t can be expressed as following:

$$F_t = 181 K N (1000 f D)^r \tag{3.5}$$

While K and r can be found from a machine handbook, values for f and D can be obtained from an NC programmer or an expert system such as CUTTECH [Barkocy 84]. An estimation of the number of cutter teeth engaged with the workpiece is important since the tangential cutting force increases in proportion with the number. For face milling, at most half of the number of cutter teeth are engaged with the workpiece. For end milling, the number of teeth is determined depending on how a cutter is engaged with the part along the cutter path. To be conservative, the maximal number of cutter teeth needs to be used in the calculation.

The equation (3.5) conservatively estimates the magnitude of the tangential force in proportion to the number of cutter teeth. That is, the total tangential force, $\sum F_t$, is estimated as the scalar summation of the tangential force at each tooth (see Figure 3-7). However, the tangential force at every tooth is acting in a different direction and the actual magnitude of vector summation of tangential forces is less than the estimation from equation (3.5). The radial cutting force, $\sum F_r$, and the tangential cutting force, $\sum F_t$, have the following relationship [Smith 89]:

$$\sum F_r = 0.6 \sum F_t \tag{3.6}$$

While equation (3.6) is valid for new inserts, the radial cutting force may increase as much as 100% or more when the inserts are worn.

The axial cutting force, $\sum F_a$, depends on both the tangential cutting force and the entering angle, β. Typically, the larger the entering angle, the smaller the axial force. The axial cutting force helps to hold the workpiece down to the base plate. For conservative estimation of clamping force, the axial cutting force may be ignored.

The feed force F_m is a combination of the tangential and radial cutting forces and its direction is the same as the feed direction. The magnitude of overall cutting force is estimated conservatively to be 1.5 $\sum F_t$ in consideration of the worn inserts.

The range of direction of the cutting force can be roughly estimated along the cutter path. The maximal number of cutter teeth engaged in a part is one half of all teeth. When less than one fourth of the cutter teeth are engaged with the part, the direction of cutting force will range within 90 degrees. When nearly half of the cutter teeth are engaged with the part, the direction will range about 180 degrees. Figure 3-8 shows the range of possible force directions at various milling operations.

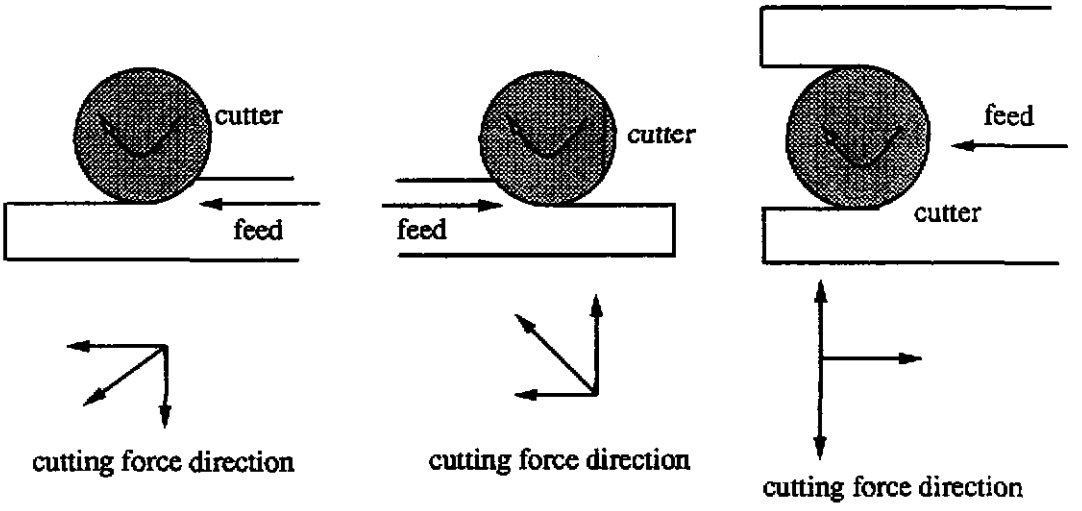


Figure 3-8: Range of possible force directions in milling operations.

3.4.2. Computation of Clamping Force

Given clamp locations and an estimation of the direction and magnitude of cutting forces, our goal is to estimate the least clamping force to maintain the force and moment equilibrium of the part during machining.

Here we have proposed a new method to estimate the clamping force. The problem is formulated as an optimization problem with constraints from static equations and a friction law to avoid any slippage at each contact. The objective function is a clamping force at a contact point between a clamp and the part. Since our goal is to achieve force and moment equilibrium with the least clamping force, the problem is to minimize the objective function. This approach is similar to Kerr's approach in computing minimal grasping force in each finger to maintain force and moment equilibrium of the object [Kerr 84].

In establishing a force model, only contacts between the part and clamping and supporting components are considered because side locating components are primarily used for locating the part and can be ignored for the conservative analysis.

The force analysis assumes the following:

- Part and fixture components are rigid.
- Clamping force is the same at every active(or clamping) contact.
- Coloumb's law is used to model friction at each contact.
- Friction coefficient is the same at every contact.

The friction coefficient between the workpiece and a fixture component may vary drastically depending on the contact surfaces' conditions and the material. The contact surfaces between the part and fixture components are wet due to a cutting fluid, and a wet friction coefficient should be used for the worst case.

Using a Coloumb friction model, the constraint equation for friction force at the ith active contact is given as follows [Kerr 84]:

$$\sqrt{A_{ix}^2 + A_{iy}^2} \le \mu N_i \tag{3.7}$$

Where A_{ix}, A_{iy} are the X and Y component of friction force at the ith contact, μ is the friction coefficient, and N_i is the clamping force at the ith active contact point. Equation (3.7) describes a cone that restricts the direction of the vector summation of two friction force components. The direction of force at the contact should remain within the cone, and the magnitude of friction force at a contact is limited by a circle whose radius is μN_i (see Figure 3-9).

Since the friction constraints from Coloumb's law are expressed as inequality equations, the optimization can be done by a linear programming (LP) method as long as constraint equations are linear. For example, the simplex method can be used when the optimization problem is formulated with linear equations [Taha 82]. The standard format for the simplex method is given in the previous section. Since the constraint equation at each contact from Coulomb's friction law is non-linear, it is linearized by a set of multiple planes. For example, an inverted pyramid within the friction cone can be used to approximate the cone.

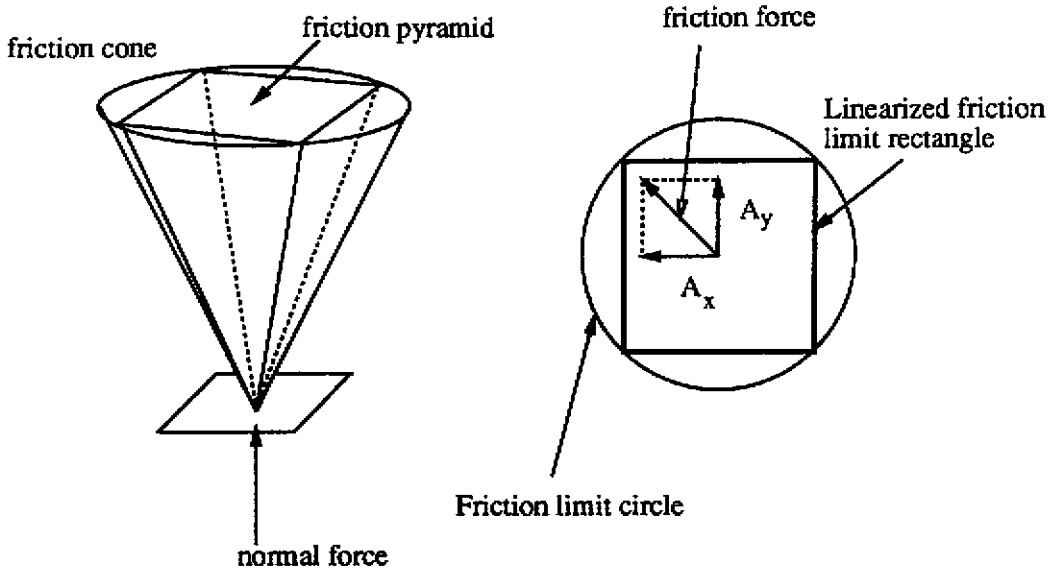


Figure 3-9: Friction cone at a contact and its linearized representation

Then, equation (3.7) can be written as the following:

$$A_{ix} - \mu N_i \le 0.$$
$$-A_{ix} - \mu N_i \le 0.$$
$$A_{iy} - \mu N_i \le 0.$$
$$-A_{iy} - \mu N_i \le 0.$$

The goal is to estimate a minimum clamping force to hold the part against every direction of the cutting forces. In fixture plans with overhead clamps or a vise, the part motion is not restrained in the X-Y plane by fixture components (see Figure 3-4). Thus, when the cutting force's direction is parallel with the base, the part equilibrium should be maintained by friction force. Since the friction coefficient at contacts between the part and fixture components is fairly small(typically 0.1 or 0.2), the largest clamping force with each cutter path is found with the cutting force direction parallel with the base.

When a fixture plan is composed of clamps and supports, every contact between the part and fixture components can be modeled as point contacts. However, the contact area between the part and a base plate (or a subplate) cannot be modeled as a point contact. For fixture plans with a vise, a part has a surface contact with jaws. Surface contacts between the part and fixture components can be approximated by discrete point contacts. When the cutting force's direction is parallel with the base, the surface contact between the part and the base (or subplate) can be approximated by point contacts underneath each clamping point. As a linear programming tool to solve the optimization problem, the simplex method may be implemented by existing routines [Press 88]. In order to further simplify the problem, we have assumed the following:

- Each clamp is supported by a support.
- Friction coefficient is the same at both active and passive contacts.
- Reactive force at a passive contact is the same as the clamping force at the corresponding active contact (clamp location).

- Friction force's magnitude and direction at a passive contact would be the same as those at an active contact.

Note that the above assumptions are made for a conservative analysis. Thus, a conservative friction coefficient should be used in consideration of the material of the part, support or the base plate, or clamps.

In a fixture plan with a vise, the part and vise jaws has a surface contact. The surface contact area is conservatively estimated by a rectangle and approximated by 3 point contacts. Each contact is assumed to apply the same amount of clamping force. Details to identify the contact area between the jaw and the part are discussed in Chapter 6. Figure 3-10 shows the 2D force model of a fixture plan with 2 clamps.

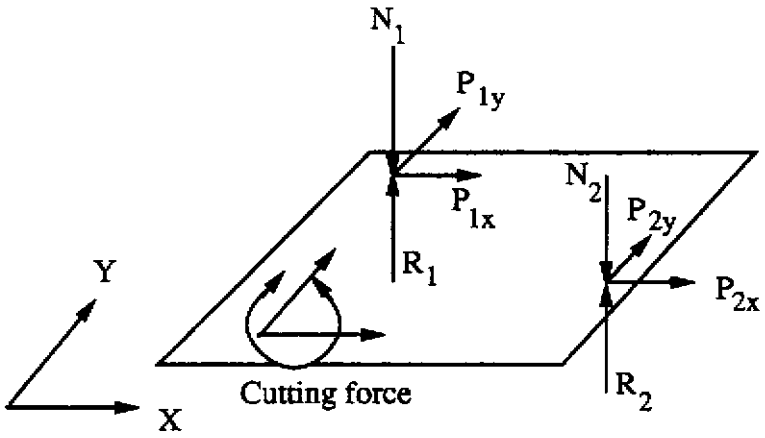


Figure 3-10: 2D force model for a cutting force direction parallel with the base.

The problem is formulated according to the standard form of simplex method [Taha 82]:

Minimize N_1

Subject to:

$$\sum F_x = 0, \quad \sum F_y = 0,$$
$$\sum M_z = 0,$$
$$P_{1x} - \mu N_1 \le 0.$$
$$-P_{1x} - \mu N_1 \le 0.$$
$$P_{1y} - \mu N_1 \le 0.$$
$$-P_{1y} - \mu N_1 \le 0.$$
$$\cdots$$
$$P_{nx} - \mu N_n \le 0.$$
$$-P_{nx} - \mu R_n \le 0.$$
$$P_{ny} - \mu N_n \le 0.$$
$$-P_{ny} - \mu N_n \le 0.$$
$$N_1 = N_2,$$
$$\cdots$$
$$N_{n-1} = N_n,$$
$$N_1, \ldots, N_n \ge 0.$$
$$P_{1x}, \ldots, P_{nx} \text{ unrestricted}$$
$$P_{1y}, \ldots, P_{ny} \text{ unrestricted}$$

Where

F_x, F_y = force components in X and Y.
M_z = moment components in Z.
n = the number of contacts.
N_i = the clamping force at ith contact.
μ = friction coefficient.
P_{ix}, P_{iy} = friction force component in X and Y at ith passive contact.

Friction force components, P_{ix} and P_{iy}, can have positive or negative values. However, every variable should be non-negative in the simplex method. Thus, P_{ix} and P_{iy} should be replaced by 2 non-negative dummy variables. For example, P_{ix} is replaced by $U_i - V_i$ for i = 1, . . . , n., where both U_i and $V_i \ge 0$.

The simplified analysis can be applied because every cutting path from milling or drilling operations has a force direction parallel with the base, regardless of the part orientation relative to a machine bed. When a part is placed on a horizontal base, each cutting force's direction from a milling operation is parallel with the base. For a drilling operation, its thrust is perpendicular to the base, but its torque is parallel with the base. When a part is placed on an angle plate, each cutter path has a cutting force direction parallel with the base. Any other force directions can be ignored in estimating clamping force since they tend not to dominate. When a part is placed on a sine table, a cutting path may not have a force direction parallel with the base. In this case, each cutting force direction is split into two force components parallel with and perpendicular to the base. Then, the clamping force is estimated with the force component parallel with the base.

For each cutting force direction, a new set of constraint equations is formulated, and the minimized clamping force is computed. Because the method is computationally expensive, it is better to include only the most critical cutting force and direction. As discussed earlier, milling operations could have diverse directions of cutting force along their paths. To speed up the computation, a few representative force directions at starting and ending points of each path can be considered.

In a fixture plan with overhead clamps, each clamp is assumed to apply the same amount of clamping force. The minimized value of the objective function is the necessary clamping force. In a fixture plan with a vise, the necessary clamping force for a movable jaw is 3 times the clamping force at a point contact. If the magnitude of the clamping force at the active contact is within the maximal clamping force of a clamp (or vise), the fixture plan is valid. The least required clamping force to hold the part rigidly during machining is the largest clamping force among the least clamping forces necessary to maintain the part's equilibrium for each cutting force.

3.4.3. Remarks

Force analysis is computationally expensive, and it is not possible to consider every force direction along each cutter path. Often, a setup may include multiple features to cut. In order to estimate the clamping force with the milling operations, various directions of cutting forces may be considered. Thus, a few representative force directions at each milling cutter path can be used to speed up the computation.

3.5. Checking part deflection

Part deflection during machining can deteriorate part accuracy and cause dynamic problems such as chatters in the cutting tool and vibrations in a part/fixture assembly, etc. For example, when drilling a hole in a poorly-supported thin part, severe part deflection not only causes the part to vibrate, but also may break the drill (see figure 3-11).

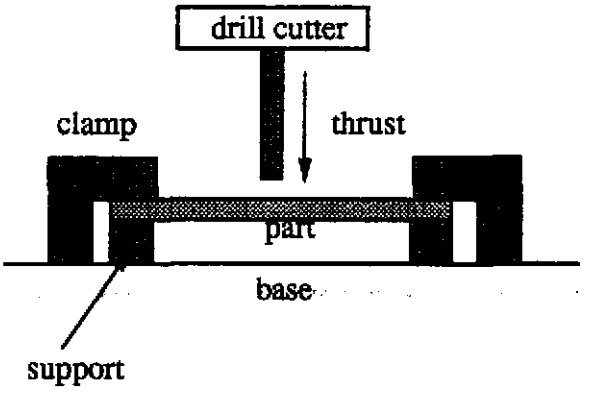


Figure 3-11: Part deflection due to drilling

When a candidate fixture plan is generated with the clamping force at every clamping component, it is necessary to check whether part deflection due to clamping force or cutting force is acceptable. The stress applied on the contact area between the clamp and the part, σ, can be estimated by

$$\sigma=\frac{F}{A}$$

where F is the clamping force and A is the contact area between the clamp and the part. For example, let us assume that a swing clamp driven by hydraulic power can apply up to 10,000 lbs force. If the contact

area is 1 square inch, the stress at the clamp location is about 10 ksi. However, if the contact area is 0.25 square inches, the stress would be 40 ksi.

If the stress due to the clamping force is larger than the lower yield point (LYP) of the part material, the clamp may deform the part. The typical value for LYP for 1020 steel is about 40 ksi (kilopounds per square inch). For pure aluminum, LYP is less than 10 ksi [Crandall 78]. If the stress due to clamping force at a clamping location is larger than LYP, the fixture plan should be rejected.

Part deflection problems typically exist when a cutting force or clamping force is applied to a thin or unsupported part area. A commercially available CAD system equipped with a finite element method (FEM) package can automatically generate a finite element mesh on a solid model of the part and can display deflection in an object which is subject to external forces. Lee and Haynes [Lee 86] have developed software with FEM to measure part deflection caused by fixturing. The software can display the geometry of a deformed workpiece under cutting forces with both fixed direction and magnitude.

However, the deflection analysis using FEM is rarely performed in practice for the following reasons.

1. FEM is computationally expensive.
   - Since the direction of cutting force may vary continuously along its path, time to measure part deflection with multiple directions would be significant.
2. An accurate model for FEM is extremely difficult to obtain.
   - Because there is no reliable way to accurately measure the direction and the magnitude of cutting forces along every cutter path, only the conservative estimation of cutting forces is available. Also the part geometry in a setup continuously changes due to material removal during machining.
3. A human expert is required to analyze the result from FEM and make an appropriate decision.
   - Even if FEM measures part deflection accurately, a human expert is required to determine the seriousness of part deflection. An experienced tool designer is able to quickly detect unacceptable part deflection by visual inspection considering the part geometry, the part material, cutter paths, and cutting and clamping forces. A human expert would make a conservative decision rather than risking any failure in a setup due to part deflection.

Direct contact between the part and a base plate is typically preferred because it quickly provides a good locating and supporting method while also preventing part deflection due to cutting force. However, the part often needs to be raised from the base due to the fixture components, cutting operation, and the part size. When a part needs to be raised from the base plate in a fixture plan with overhead clamps, supports or a subplate are placed under the part. For a fixture plan with a vise, parallel bars are placed under the part.

If supports are used in a fixture plan with overhead clamps, each support should be placed under a clamp to prevent any deflection due to clamping force. When cutting or clamping forces are directed toward the base plate in a fixture plan with overhead clamps, some of the unacceptable part deflection can be prevented by placing extra supports or a subplate under the part. Thus, the decision on which method is used to support the part is made by a human expert after careful evaluation of the part deflection by considering the magnitude and direction of cutting and clamping forces.

When a cutting force or clamping force is directed toward the region that cannot be supported at all by fixture components, part deflection may be unacceptable. Figure 3-12 shows some cases where part deflection due to cutting or clamping force is difficult to prevent with modular fixture components. When a candidate setup is suggested, a human expert may detect such part deflection by investigating part geometry and cutting forces before generating fixture plans.

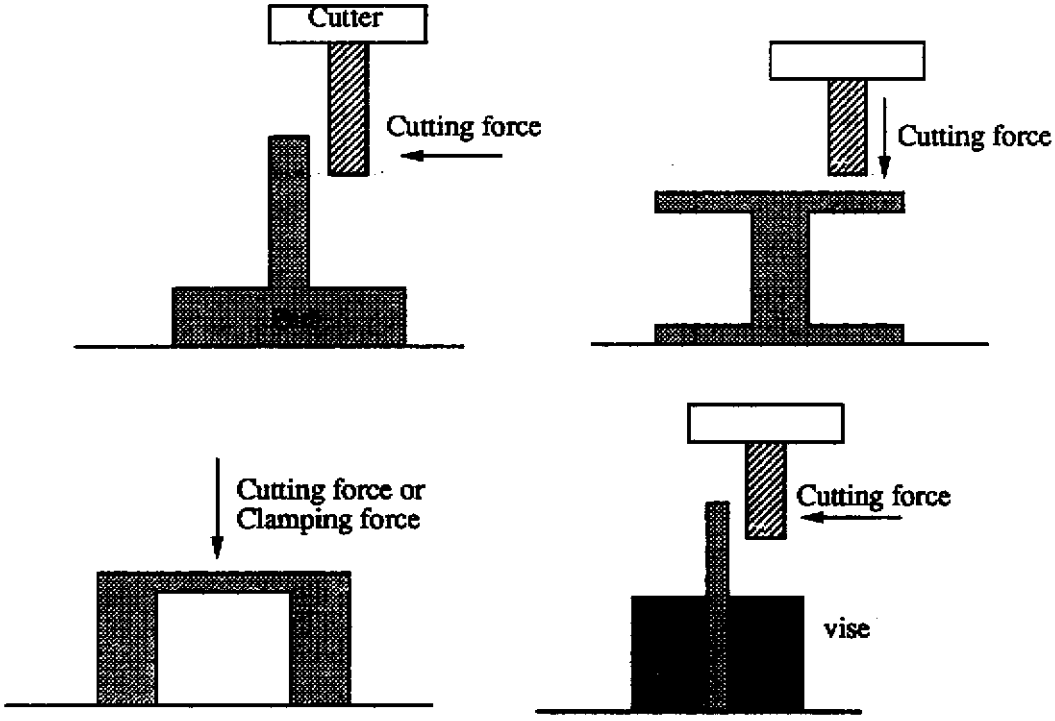


Figure 3-12: Part geometries that are likely to deflect due to cutting force when the magnitude of the cutting force is large

3.6. Summary

In this chapter, various analytical tools have been presented to automatically check fixturing requirements. While interference checking and part rotation checking due to clamping can be done rather precisely, a computation of the clamping force and part deflection checking need to be done conservatively because it is not possible to establish accurate models for the analysis. When incorporated into a system that generates fixture plans, these tools can be used to automatically identify valid fixture plans with either clamps or a vise.

Chapter 4
A System for Automated Fixture Planning

4.1. Introduction

In this chapter, we describe a system that can automatically generate fixture plans using modular fixture components with minimal human assistance. Fixture components in a modular fixture library can be categorized as either primary or secondary components; the primary components are used to locate, support, and clamp the part, while the secondary components are used to provide flexibility in the installation of primary components. Primary components are clamps, vises, parallel bars, locators, and supports while secondary components are risers and installing bolts, etc.

A vise is the most cost-effective fixture and it is used widely in practice. However, its use is limited to the rectangular part shape, and a vise may not be suitable to hold the part when cutting operations are complex. Most clamps can be classified as either overhead clamps or side clamps. While overhead clamps apply their clamping force perpendicular to the base plate, side clamps apply force to the part which is parallel to the base plate.

Although side clamps can provide cutters good access to the part's top surface, due to its limited usage, they are not as widely used as over clamps or a vise. While previous research on the automated fixture planning has only considered fixture planning with clamps, we have considered fixture plans with both overhead clamps and a vise.

Section 2 describes the proposed system for automated fixture planner. Section 3 discusses several assumptions used in the system. Section 4 describes the necessary inputs for the system. Section 5 describes a procedure for a human expert to select the most favorable fixture plan among multiple fixture plans generated by the system. Section 6 makes several remarks related to the application of the system.

4.2. Overview of the System

To develop a system that automatically generates fixture plans, intelligent reasoning schemes based on fixture planning practices should be developed first so that cost-effective and practical candidate fixture plans may be generated. In each candidate fixture plan, every fixture requirement should be checked automatically by analytical tools to reduce or eliminate human intervention.

4.2.1. Current Fixturing Practice

Fixturing is composed of clamping, locating, and supporting. Clamping is the most critical process in the fixture planning since it is strongly related to fixturing cost and part deflection. While insufficient clamping force would not hold the part during machining, excessive clamping force might deflect the part. When generating a fixture plan with overhead clamps, a tool designer typically performs clamping plan as follows:

1. Estimate the most critical cutting force.
2. Estimate the necessary clamping force.
3. Select the clamp types and determine the number of clamps.
4. Determine the locations for clamps.

The fixture planning procedure with a vise is similar except that a single vise is used to clamp the part. Once the most critical cutting force is estimated, a tool designer estimates clamping force using the Coloumb's friction law without considering exact locations of clamps or a vise. In order not to risk any failure in holding the part during machining, the magnitude of clamping force is usually increased by a conservative safety factor. A clamping component, either an overhead clamp or a movable vise jaw, is limited in its maximum clamping force and in its available numbers. For example, when generating a fixture plan with overhead clamps, the type and number of clamps should be determined considering the necessary clamping force. Clamps are placed as widely apart as possible from each other to maintain the part's equilibrium against moments caused by cutting forces.

The current clamping practice tends to use more clamps or apply a larger clamping force than necessary. This may hinder cost-effective fixture planning and process planning. That is,

- If the batch size of a part is large and a setup requires a fixture plan with clamps, time spent during clamp assembly would be significant due to the large number of clamps.
- A large clamping force may deform or deflect the part when the clamp location is not well supported.
- A large number of clamps in a fixture plan often limits cutters' access to features to be machined. As a result, a fixture plan may not be generated for a candidate setup, forcing the setup planner to increase more than necessary the number of setups.

In order to generate cost-effective fixture plans for a given setup, we have proposed an algorithmic approach where various candidate clamping plans are generated, and the minimum clamping force is estimated with the more accurate analytical tool which is discussed in Chapter 3.

4.2.2. Proposed Fixture Planning Strategy

As noted in Chapter 3, the detection of unacceptable part deflection due to either cutting or clamping force is difficult due to poor analytic models. A human expert is required to check for part deflection in fixture plans. A human expert could be either a setup planner or a tool designer. In order to speed up the process, it is desirable for a setup planner to directly interact with the system. However, if the setup planner has little or no experience in fixturing, a tool designer is required to help the setup planner with

checking part deflection and selecting a favorable fixture plan. Figure 4-1 shows the architecture of the system.

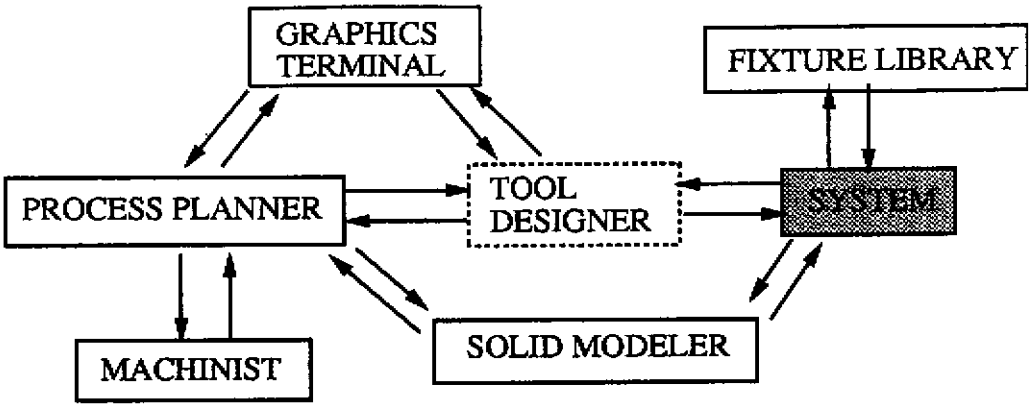


Figure 4-1: System architecture

For some setups, part deflection due to cutting force may not be prevented regardless of fixture plans. Thus, it is desirable for a human expert to check any part deflection due to cutting force before generating any fixture plans. A human expert can detect unacceptable part deflection due to cutting force by carefully viewing the part geometry and cutter paths displayed on a graphics terminal and considering the cutting force and direction along the cutter paths. If part deflection does not exist, the system can be applied to generate fixture plans. If part deflection does exist, a setup planner may reduce the magnitude of the cutting force responsible for deflection by consulting with a machinist or change the setup.

This system consists of two algorithms for the generation of fixture plans with clamps and a vise. Depending on the part geometry, cutting plan, and fixture components, the system may generate fixture plans with clamps and/or a vise. A human expert is required to select the most favorable fixture plan. The selected plan should not have the problem of part deflection due to the cutting and/or clamping force.

The system automatically generates valid fixture plans with either clamps or a vise which satisfy the geometric, kinematic, and force constraints of the fixture requirements. While the algorithm for fixture plans with a vise typically generates just a few plans, the algorithm for fixture plans with overhead clamps can generate numerous plans if there exist many clampable locations on the part. Although each fixture plan meets fixture requirements such as geometric, kinematic, force constraints, it may not be qualified as a valid plan if it has part deflection problems and/or violates any other constraints during the fixture assembly and machining.

In order to select the most favorable fixture plan, a human expert should view the simulated part/fixture assembly of each fixture plan on a graphics terminal, starting from the plan most highly rated by the system. A human expert should select a fixture plan with the minimum clamping force that does not have any deflection problems and satisfies all other constraints. If he/she detects unacceptable part deflection due to either cutting or clamping force, the current fixture plan should be rejected, and the other fixture plan should be viewed for inspection. It can take a long time for a human expert to select a favorable plan especially when part deflection problem exists in highly rated fixture plans.

The fixture plan with a smaller clamping force will have little part deflection even when a clamp in the fixture plan is not directly supported underneath. At the same time, this rating has additional advantage in that there is a larger safety margin between the required clamping force and the clamp's physical limitation. In order to reduce the selection time, the system rates each plan according to the magnitude of required clamping force. The smaller the clamping force, the higher a fixture plan is rated by each algorithm. Typically, a human expert would inspect fixture plans starting from the most highly rated fixture plan. If the fixture plan does not have any problems, it will be a near optimal fixture plan for a human expert to select.

When the part is raised from the base in a candidate fixture plan with overhead clamps, the algorithm tentatively places a support underneath each clamp, if the part geometry permits. If a cutting force causes part deflection in the fixture plan, a human expert can add extra supports or use a subplate instead in order to prevent part deflection. When a fixture plan with a vise has part deflection problems due to clamping force or cutting force, it cannot be used at all since there is no way of preventing part deflection with modular fixtures.

4.3. Description of Algorithms

In this system, an algorithm for automated fixture planning has been developed first with overhead clamps and then with a vise. For a given setup, multiple fixture plans with either clamps or a vise are generated by considering all the fixture requirements other than the part deflection. The algorithm for fixture plans with overhead clamps generates clamping plans before locating and supporting plans. The algorithm for fixture plans with a vise generates clamping plans before supporting plans with parallel bars.

First, each algorithm identifies every possible location for a clamp (or a vise) on the part considering clamping principles and applicable fixture constraints. Second, each algorithm then exhaustively generates candidate fixture plans based on intelligent geometric reasonings developed in the algorithm. Third, each algorithm prunes invalid plans by evaluating each plan against fixture constraints. Each candidate location for a fixture component or each candidate plan is checked against fixture requirements such as the interference problems, any part rotation due to clamping, and clamping force with the exception of part deflection.

Fixture constraints are applied such that the search space is quickly reduced by more precise analytical methods during the generation of candidate fixture locations and fixture plans. Because interference checking and kinematic checking can be analyzed quickly and precisely, they are used to prune invalid fixture locations and plans before checking the magnitude of estimated clamping force against the clamp's (or vise) maximum force limitation.

Details of algorithms for automated fixture planning with overhead clamps and a vise are described in Chapter 5 and 6, respectively. Each algorithm has been written into a algorithm and examples for the generation of fixture plans with selected setups are given in Chapter 7.

4.4. Assumptions

The fixture planning process with a CAD-based fixturing system may vary depending on available fixture components in the modular fixture library, the cutting tool, and a human expert's past experience.

Several assumptions have been made to 1) speed up the computation during requirements checking in each candidate fixture plan , 2) reduce the search space for fixture locations to a manageable size considering practices of an experienced tool designer, or 3) generate practical plans in consideration of the capability of the modular fixture library.

1. The geometric reasoning assumes machining by a 3 axis vertical milling machine.
2. The part's orientation is specified by a rotation angle about either the X or Y axis of the machine coordinate. The angle range is between -90 and +90 degrees.
3. The system only considers fixture plans with overhead clamps or a vise as active components.
4. The part has three mutually perpendicular reference surfaces in order to accurately locate the part by the 3-2-1 rule.
5. A fixture plan with overhead clamps
    a. The same clamp type is used in a fixture plan.
    b. Each clamp in a fixture plan applies the same amount of clamping force to the part.
    c. A modular fixturing system is flexible enough to install fixture components at any location with specified orientation on a base plate.
    d. Supporting components such as supports or parallel bars are placed against the part's bottom reference surface (resting surfaces).
    e. Height-adjustable supports are not considered in a modular fixture library.
6. A fixture plan with a vise
    a. A movable jaw's clamping force is evenly distributed throughout the contact area on the part.
    b. Modular parallel bars with the same length and thickness are used and placed against the vise jaws.

4.5. Part Locating

The purpose of part locating is to accurately identify the position and orientation of the part in the machine coordinate so that machining accuracy is guaranteed within the specified tolerance by a designer. Today's CNC machine has the capability to measure the part to an accuracy of within one tenth of one thousand of an inch (0.0001") [Gouldson 79]. Thus, the accuracy of a machined part does not rely on the CNC machine or its operator, but on how accurately the part is located.

Because the part accuracy is critical in most metal cutting operations, it is important to accurately reference features against a reference datum in each setup. Part zero specifies the location of part origin in the machine coordinate. The location of part zero is partially determined by the system and completed by a human expert so that the part/fixture assembly is properly situated on the base plate. Details on how to determine the location of the part zero in fixture plans with overhead clamps and a vise will be discussed in Chapter 5 and 6, respectively.

A prismatic part is typically located according to the 3-2-1 rule. The 3-2-1 rule can be achieved by supports and locators with or without the aid of a touch probe. When locators and supports are used to completely locate the part, the 3-2-1 locating rule requires that the number of contact points on a part's reference plane must be greater than or equal to three in one plane, greater than or equal to two in another plane, and greater than or equal to one in the third plane (see Figure 4-2).

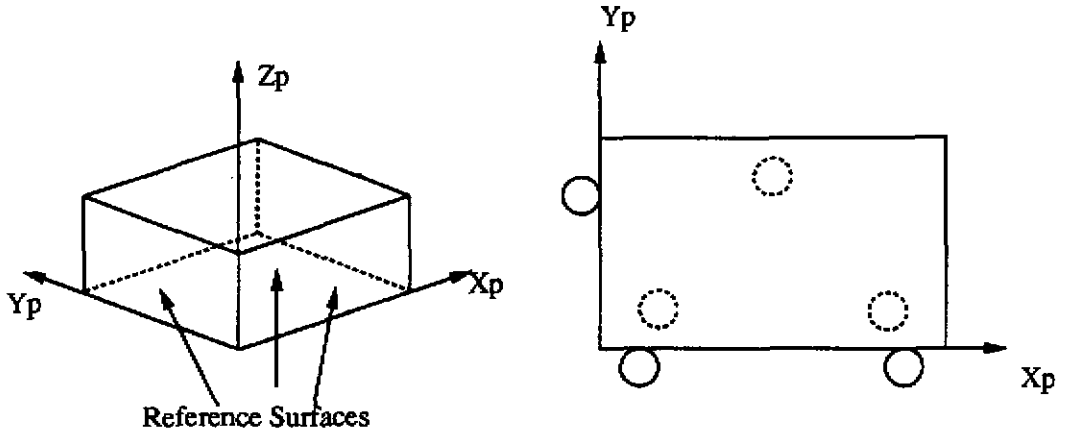


Figure 4-2: The 3-2-1 locating rule

In a fixture plan with clamps, locating a part with the 3-2-1 rule can be done by a mixture of various components such as locators, a fixture base, supports or a subplate. Since a fixture base or supports provide greater than or equal to 3 point contacts against the part's bottom reference surface, at least 2 locators must be placed against a side reference surface, and at least 1 locator must be placed against another side reference surface. Locating by the 3-2-1 rule with fixture components typically provides faster locating and better machining accuracy than locating with a touch probe. Thus, a fixture plan that can be completely located by fixture components is usually favored.

In order to take advantage of the 3-2-1 rule, the part has three mutually perpendicular reference surfaces to accurately reference features. The part's reference surface parallel to the base plate is called a resting surface. It is also considered a major reference surface of the part since it is usually the largest reference surface. When a sine table or angle table is used and the part's reference surface is exposed to cutters, locators may not be placed because the part overhangs the base. Thus, the part is partially located by two locators on a minor reference side, and a touch probe should be used by probing another minor reference side to complete locating (see Figure 4-3).

In a fixture plan with a vise, parallel bars or a base plate provides 3 point contacts on a rest reference surface, and a fixed jaw provides 2 point contacts on a side reference surface. A stop can be installed against the part's other reference side to completely locate the part, or a touch probe needs to be used to probe the other reference side.

Cutter paths for each feature are generated in the part coordinate. Once the part's location and orientation is known in the part coordinate, coordinates of cutter paths are transformed into the machine coordinate, and NC codes for each cutter path can be generated by either an NC programmer or an expert system.

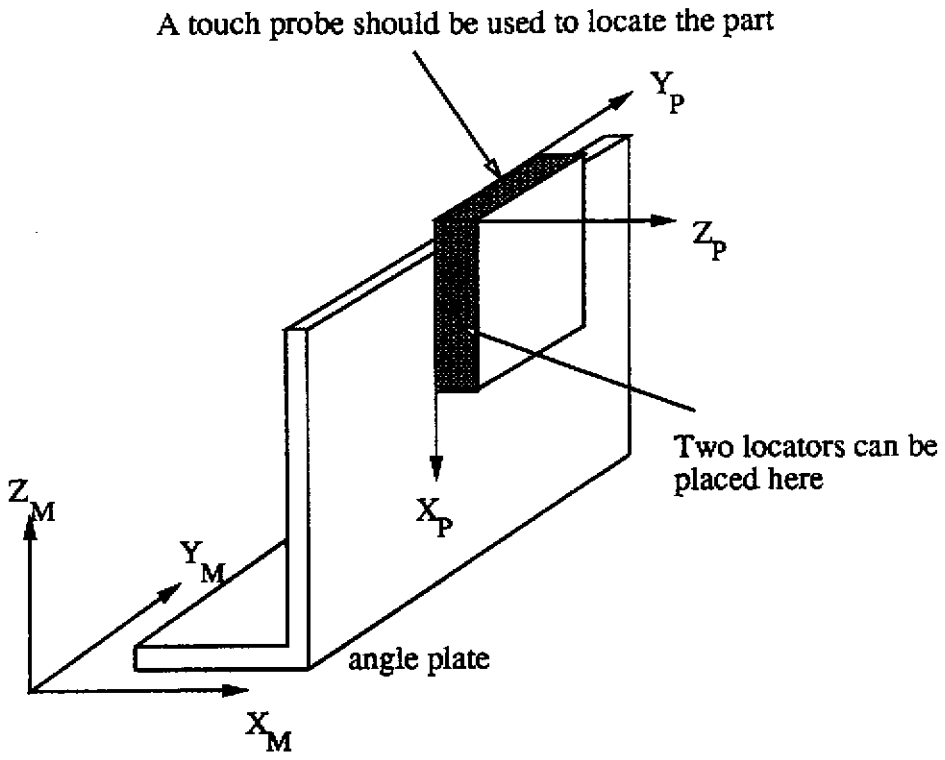


Figure 4-3: Part orientation that does not allow locator placement on a reference surface

4.6. Description of inputs

The system requires input on the part geometry, the magnitude and direction of cutting forces, cutter paths, cutter diameter, and the geometry and limitation of every component in a modular fixture library. The geometries of part, swept volumes, and fixture components are described by boundary representation for the geometric reasoning used in the system. Part geometry and the coordinates of cutter paths are described in the part coordinate. The geometry of fixture components is first constructed in each local coordinate. Once the position and orientation of a fixture component is specified by the system, it can be transformed into the part coordinate.

4.6.1. Part description

The algorithms require the part geometry described in boundary representation (B-rep). The geometry of a stock, geometries of features to be cut in the setup, part orientation relative to the machine bed, and three reference sides should be provided. Then, the solid model of the part geometry for a setup can be constructed using a Boolean operation by taking primitive features such as cylinders and blocks out of a rectangular stock.

In each setup, two types of the part geometry are available - pre-machined part geometry and post-

machined part geometry. While the pre-machined part geometry is generated by considering only those features already made before the given setup, the post-machined part geometry is generated by considering features to be made for the given setup.

While either pre-machined or post-machined part geometry can be used for fixture planning with a vise, a fixture plan with clamps may have problems, depending on the features to be cut in the setup. With the pre-machined part geometry, some clamps (and supports) may be placed on the material which will be removed. With the post-machined part geometry, locating can be a problem because there may not be reference surfaces for locators. Figure 4-4 shows problems with two different part geometries. Thus the system uses both part geometry descriptions - the post-machined part geometry for the clamping plan and the pre-machined part geometry for the locating plan.

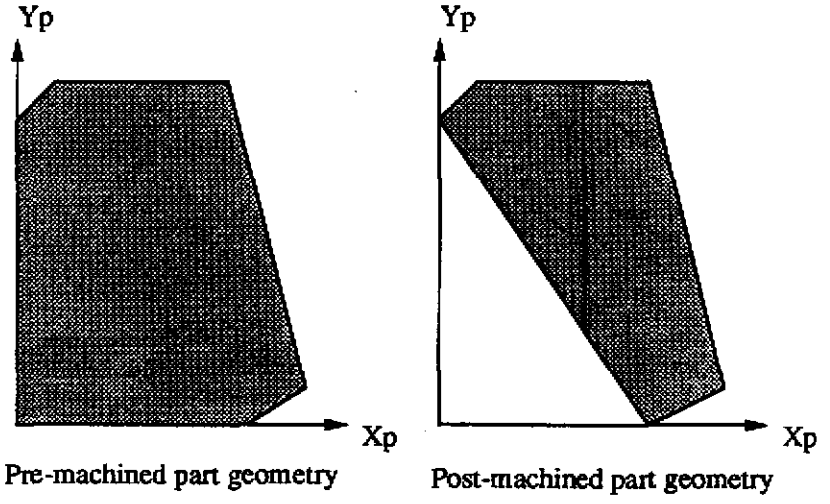


Figure 4-4: Part geometry before and after machining

Part orientation

In order to simplify geometric reasoning for locating and supporting in the algorithm, the system requires that the major reference surface of the part lies on the X-Y datum plane of the part coordinate, and two minor reference surfaces lie on the Y-Z and X-Z datum plane.

Figure 4-5 shows how the part's reference surfaces should be oriented in the part coordinate. Part orientation is specified relative to the machine bed by some angle about either the x or y axis of the machine coordinate. This is determined by a setup planner when grouping features in a setup.

When the angle is equal to 0^o, a horizontal plate is used. When the angle is equal to either positive or negative 90^o, an angle plate is used. A sine plate is used when a horizontal or angle plate cannot be used. Currently, the algorithm for fixture planning with a vise only considers the part oriented by less than 45^o due to difficulty in assembly. If the part/fixture assembly can be done in horizontal position and can be rotated to the specified angle, this assumption should be removed.

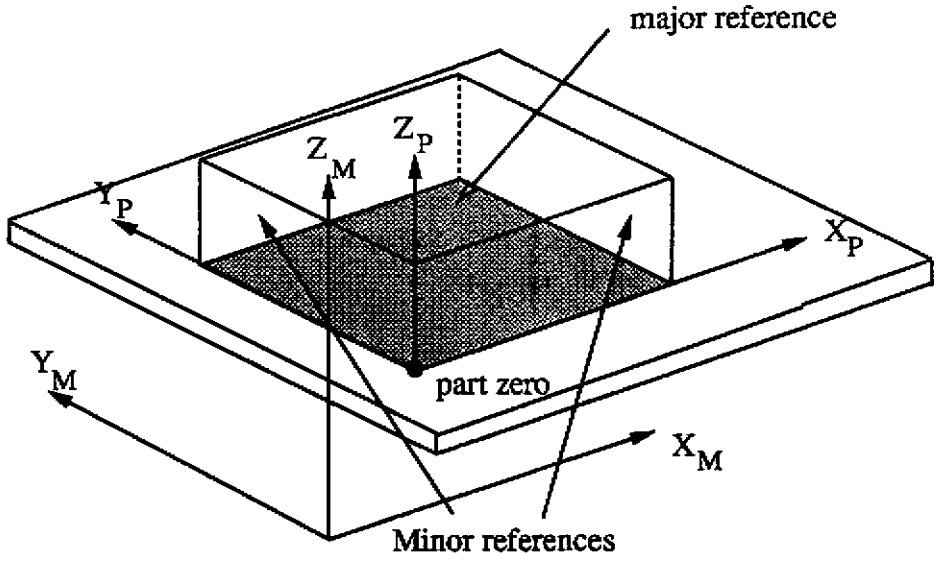


Figure 4-5: Reference surfaces of the part, and the location of the part zero on a horizontal base

4.6.2. Cutting plan

The cutting plan for each feature can be provided by a machinist or an expert algorithm such as CUTTECH [Barkocy 84]. A cutting plan includes the cutter diameter, the coordinates of starting and ending points in the part coordinate, and the magnitude and direction of cutting force.

In a milling machine, each feature is machined by face milling, end milling, or drilling operation, etc. A cutting plan for a feature is typically composed of multiple cutter paths. The most computationally expensive process in the system is estimation of the clamping force. Because the time in estimating clamping force increases proportionally with the number of cutter paths, the cutter path with the largest cutting force is used when a feature requires multiple cutter paths with the same direction. Typically, the cutter path responsible for removing the material by rough cutting applies the largest cutting force to the part. Cutting force and torque are conservatively estimated for the worst case. A bounding swept volume which represents cutter paths is constructed for each feature in order to speed up the interference checking against fixture components.

A straight cutter path is described by coordinates of the starting and an ending point. A circular path is described by a center coordinate of the path as well as a starting and ending point coordinates.

Fixture components in a fixture plan should be placed on or around the part without interfering with the swept volumes of cutter paths. Because a cutter is attached to the spindle, the true swept volume would be the space which the cutter and the spindle sweeps along the path. When a drill cutter or a milling cutter make deep holes or slots, a cutter spindle may interfere with fixture components (clamps or vise jaws). Currently, the system constructs swept volumes of cutters neglecting the cutter spindle in order to speed up interference checking and provide a human expert a better view of part/fixture assembly in the presence of

cutter paths. For the complete interference checking between fixture components and cutter paths, the spindle can be easily included into the swept volume.

The swept volume of a straight cutter path is modeled as a rectangular box, based on the cutter's diameter and the starting and ending coordinates of the path. The swept volume's height is considered to be infinite because the cutter is part of the cutting machine. The swept volume is first constructed in the local coordinate in which X axis is along the cutter path. Then, its geometry is transformed into the part coordinate according to the orientation of the cutter path.

When a cutter path is circular, the precise representation of its swept volume would require many faces and take much time for the interference checking. For fast interference checking, a circular path is first approximated with a few straight paths and each segment of a straight path is then described by a rectangular box. Figure 4-6 shows swept volumes of a straight path and a circular path. Since the system assumes a 3-axis vertical milling machine, each cutter path in milling operation is parallel to the X-Y plane of the machine coordinate, and the path in a drilling operation is perpendicular to the X-Y plane.

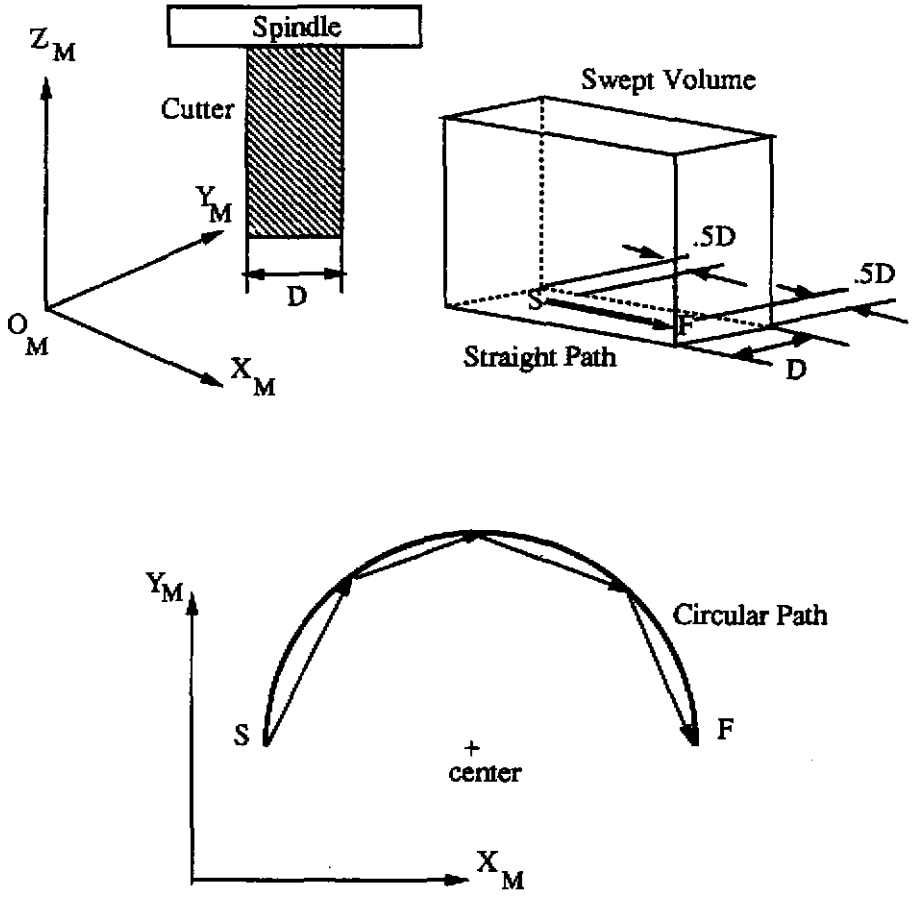


Figure 4-6: Swept volumes of a straight path and a circular path

Cutting force and direction

Chapter 3 discussed formulas used to estimate the magnitude of the cutting force for drilling and milling operations. In drilling operation, the magnitude of cutting force can be estimated rather precisely, and its thrust is in a single direction. However, in milling operations, the magnitude and direction of the cutting force vary depending on how the cutter is engaged with the part and the condition of the cutter. Thus, it is not possible to accurately estimate either the magnitude and the direction. The magnitude should be estimated conservatively for the worst case, and multiple directions along each path should be considered.

In both drilling and milling operations, a feature typically requires multiple paths for roughing and finishing. While the direction of major thrust for a drilling operation is single, the direction of cutting force for milling operations can vary along the path.

A mathematical tool used to estimate clamping force for a fixture plan is computationally expensive. Computation time would increase with the number of cutter paths and their directions of cutting forces. Thus, the system considers only the critical path (or the path with the largest cutting force) when multiple cutter paths are required for a feature. When a cutter travels along the path, fixture components should not interfere with the cutter. The space generated by the cutter is called as swept volume. A path with the lowest z coordinate is considered for the construction of the swept volume while it assumes the largest cutting force among the cutter paths.

In order to accurately estimate the clamping force and detect part deflection, every direction of cutting force should be considered along the path. Since computation time increases proportionally with the number of directions of cutter forces, a few representative force directions are used for the cutter path in order to speed up the computation. Currently, the system considers a few directions within the possible range of force direction at the starting and ending points of a cutter path. Figure 4-7 shows the cutting force directions used to estimate clamping force for a fixture plan. Three force directions are considered at both the start and finish coordinate of a cutter path. Note that these directions are perpendicular to the spindle in the 3 axis milling machine. Directions at intermediate points on the cutter path between the start and finish points are ignored. In our future research, we will consider a more precise estimation of the direction range of the cutting force.

4.6.3. Fixture library

A modular fixture library consists of various components that can be categorized as locators, supports, and clamps. A fixture base plate has either pin holes or T slots, and each component in a specific modular fixture library is designed so it can be installed on the base by using either T slots or pin holes. There are three types of fixture base plates: a horizontal plate, a sine plate, and an angle plate. The part orientation is determined by a setup planner or a setup planner depending on the orientation of part's resting surface(s) relative to the machine bed.

A horizontal plate is used when the part's resting reference surface is parallel to the machine bed. A sine

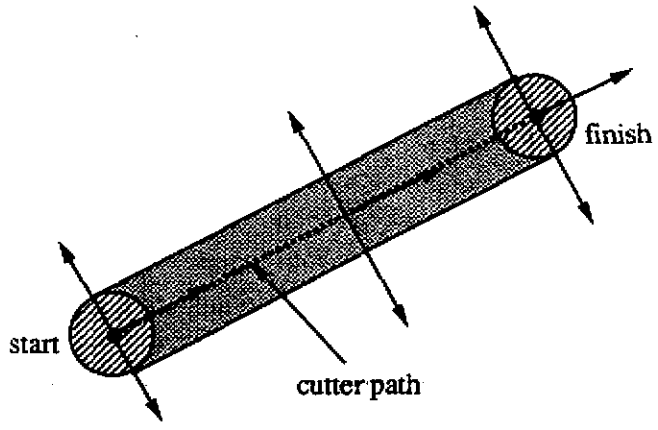


Figure 4-7: Force directions used to estimate clamping forces

plate is used when the part's resting reference surface needs to be oriented at an angle other than ±90 degrees. When the part's resting surface is oriented by ±90 degrees about the X or Y axis of the machine coordinate, an angle plate should be used. When a sine plate or angle plate should be used, fixture components can be assembled on the plate oriented either at the specified angle or at its horizontal position depending on the machine bed. When the fixture assembly is done on the horizontal position, the sine table is then rotated to the specified angle.

The system only considers overhead clamps such as strap clamps or swing clamps (see Figure 4-8), since they are the clamp type most widely used in practice. The operation of a strap clamp is similar to that of a lever. The fulcrum is positioned so that the clamp bar is parallel to the fixture base plate and the effort (threaded screw) is used to activate the clamp for manual operation. Power devices such as hydraulic or pneumatic systems can also be used for automatic operation. A cylindrical ram is a widely used hydraulic cylinder for automatic operation. A strap clamp's horizontal reach is adjustable by moving the clamp bar. A swing clamp is useful for applications where the clamp must be completely away from the part during loading and unloading the part.

An overhead clamp has a minimum and maximum clampable height due to its physical limitation. The maximum clampable height is limited by available risers in the fixture library. Since the time needed to check interference between objects increases with the number of faces, a simplified geometry is used to model each fixture component for faster computation. For example, overhead clamps such as swing clamps or strap clamps can be easily modeled as L-shaped polyhedra for simplified representation (see Figure 4-9).

A CAD system for fixture planning stores the exact dimension of every fixture component in a data base. Each component for a fixture is then retrieved by a human expert and placed at a specified location and orientation. However, a typical overhead clamp's geometry can vary in height in order to provide clamping flexibility. Also, a strap clamp can vary in horizontal length. A human expert should specify a proper height and an extension in order to display the geometry of a clamp in space. Supports or locators are either cylinder or block shapes. For faster analysis and simpler graphic representation, they are modeled as blocks. The geometry of vise jaws and parallel bars are also represented as blocks with fixed dimensions without approximation (see Figure 4-10).

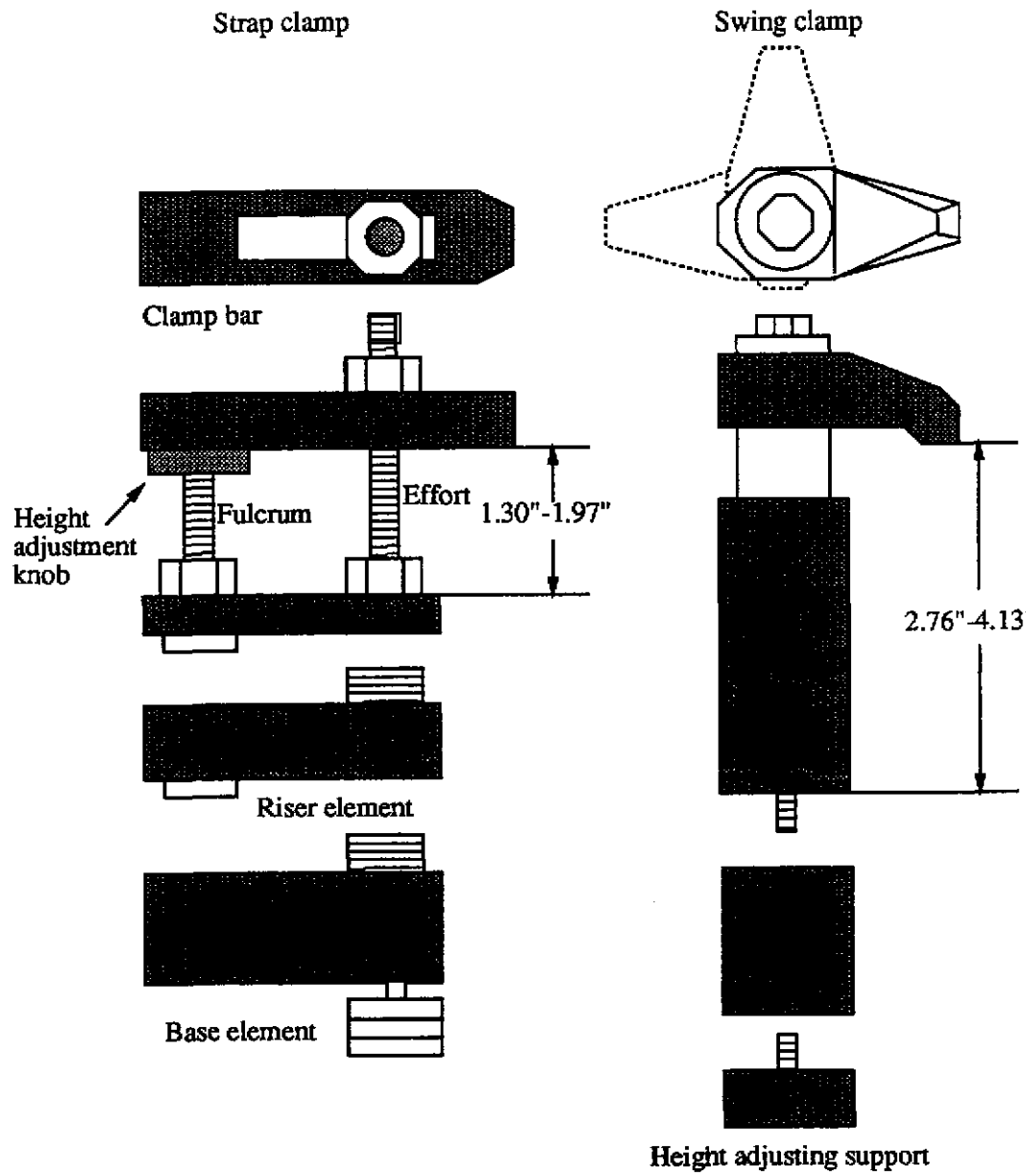


Figure 4-8: A strap clamp and a swing clamp

In the system, fixture components in the modular fixture library are stored into 4 different data base for clamps, locators, supports, and vises. Each fixture component in the data base is described by parameters such as available numbers, dimensions (length, height, etc.) of geometry, and physical limitations (for instance, minimum and maximum clampable height, maximum clamping force, and maximum extendible length of the clamp bar). This representation enables the algorithm to search and select the necessary fixture components while automatically determining the value of variables such as clamp height, clamping force, etc. At each clampable location, the clamp's height and extendible length is heuristically determined by the algorithm in consideration of requirements for clamping. Another advantage of the representation is that a human expert can quickly establish data bases for a modular fixture base using simple polyhedra or

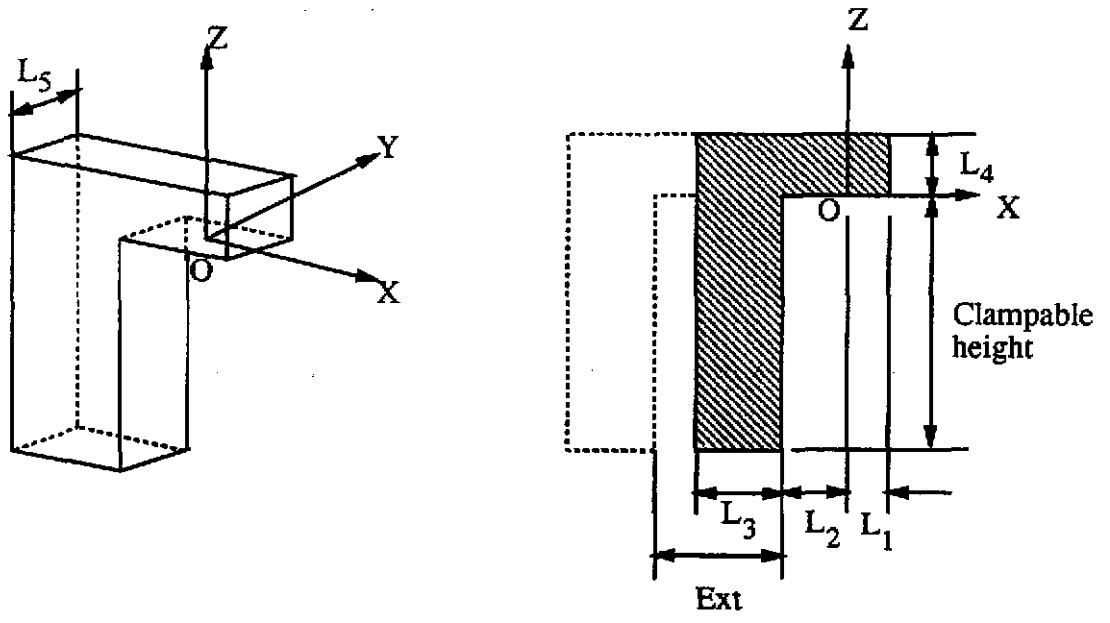


Figure 4-9: A simplified geometry of an overhead clamp

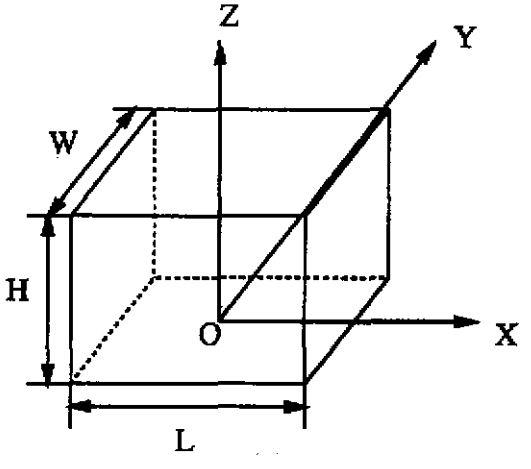


Figure 4-10: Simplified geometry of supports, locators, vise jaws, and parallel bars

easily update the existing fixture data base. Figure 4-11 shows the database for various fixture components. The unit of force is pounds, and the unit of length is inches.

The fixture data base can be easily updated from time to time according to the availability. Although the system currently does not consider plans for parallel bars and risers, they can also be put into the respective data base. Then, necessary combinations of parallel bars can be chosen from the data base in order to raise the part in a fixture plan with a vise. Also risers can be chosen from its data base in order to raise the clamp to the specified height. There is no need to perform interference checking between risers and the part since risers are placed under each clamp.

Once the location and orientation of a fixture component is specified by the system in the part coordinate,

<Data base for clamps>

Type	No.	L1	L2	L3	H	W	Ext	Min_h	Max_h	Force
strap	4	.5	1	3	1.5	.5	1	1	12	2000
swing	5	.3	.6	1.5	2	.5	0	2	10.5	3000

.
.

<Data base for supports>

Type	No.	Height	Length	Width	Diameter
Box	8	1	1	1	0
Cylinder	6	.5	1	1	1

.
.

<Data base for locators>

Type	No.	Height	Length	Width	Diameter
Box	4	1	.5	.5	0
Cylinder	4	.5	1	1	1
Box	4	2	1	1	0

.
.

<Data base for vises>

Type	H	L	Fix_W	Mov_W	Max_dist	Max_Force
Modular	4	6	2	2	8	6000
Modular	2	4	2	2	8	4000

.
.

Figure 4-11: Data bases for various fixture components

the geometry of the fixture component is first constructed in its local coordinate and then transformed into the part coordinate. Note that if locators and supports are cylinder types, the location is sufficient to transform the geometry from the local coordinates to the part coordinates. Figure 4-12 shows how a fixture component is positioned in the part coordinates.

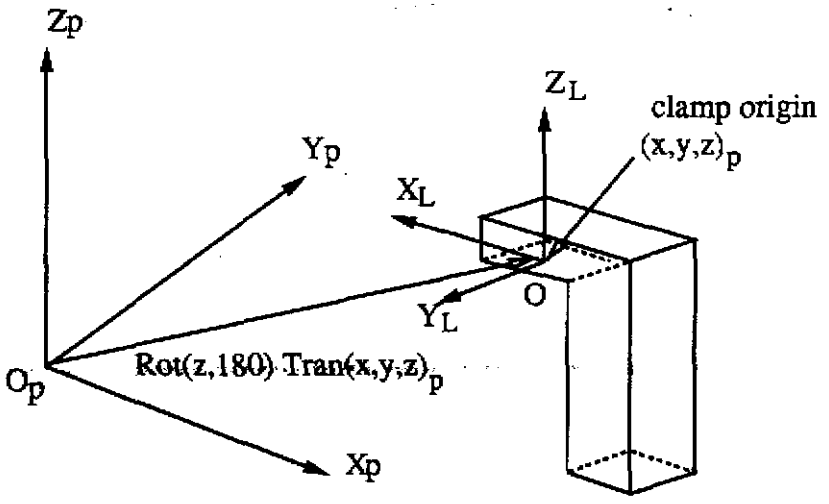


Figure 4-12: A fixture component in the local and part coordinates

4.7. Selection of Fixture Plans

Since the system does not consider the problem of part deflection, it is necessary for a human expert to detect unacceptable part deflection due to cutting or clamping force. Detecting an unacceptable deflection in the part is a very difficult task since it is related to part material, part geometry, cutting force, and the location and magnitude of the clamping forces. The more experienced the human expert, the better the decision he/she can make. The decision on part deflection should be made conservatively to ensure part accuracy during machining. If the human expert suspects part deflection, he/she should assume part deflection to avoid any failure during actual machining and to ensure part accuracy.

In order to check part deflection in a fixture plan generated by the system, a human expert can view the simulated part/fixture assembly on a graphics screen. Although actual fixture component's geometry can be used for a realistic view, the system currently displays simplified fixture geometry for faster graphic interaction.

When the part is raised from the base plate in a fixture plan with clamps, the system tentatively selects proper supports, and places them underneath each clamp if the part geometry permits. The part may not be supported properly due to the lack of supports, or an unsupported clamp may rotate the part during assembly. In either case, a human expert should add extra supports. For example, when a fixture plan is generated with 2 clamps and the part needs to be raised from the base, the system would place at most 2 supports underneath the clamps. Thus, a human expert should add extra supports to stably support the part. If the plan requires many supports to prevent part deflection or supports get in the way of cutter paths, a subplate can be used instead. Note that the system does not use height adjustable supports to raise the part or support clamps. The detection of instability can be checked easily, and the system can issue a warning for a human expert to add supports or use a subplate.

The part needs to be raised when the clamp type's minimum clampable height is larger than the part

thickness. If the part is supported by supports, the cutting force from the drilling thrust may not only cause severe part deflection, but also may break the drill. (Figure 4-13) Thus, a machinable subplate should be used to prevent the deflection. The size of a subplate should be determined so as not to interfere with clamps and locators. The thickness of the subplate should be the same as the supports' heights determined by the system.

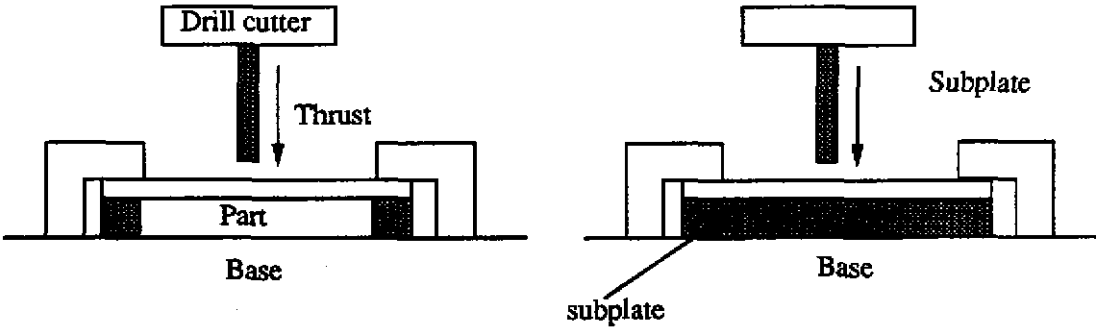


Figure 4-13: Prevention of unacceptable part deflection by a subplate

If part deflection in a fixture plan cannot be prevented by support, the plan cannot be used. A human expert should search for the fixture plan without part deflection problems.

When there are multiple plans satisfying all the fixture requirements, a human expert may prefer one plan to another due to the relative difficulty of assembly and other constraints imposed during machining. For example, a fixture plan with clamps may require the use of a touch probe to complete the part location while another plan allows the part to be located by 3-2-1 locating rules. Since the touch probe locating is less accurate and takes more time, a human expert would prefer a plan that locates the part only with locators.

4.7.1. Position and Orientation of Part

The system generates fixture plans in the part coordinate. When a part is placed on a horizontal base plate, it is assumed that the part/fixture assembly is done so that the part coordinate's datum plane is parallel to its corresponding datum plane in the machine coordinate.

If a part needs to be placed on either a sine table or an angle plate, a human expert should determine the location of the part zero and the axis of rotation so that the part geometry is properly positioned and oriented in the machine coordinate. Rotation is allowed up to 90 degrees about either the X or Y axis of the machine coordinate. One of the side reference surfaces of the part is always parallel with the X-Z or Y-Z datum plane of the machine coordinate.

Once the part zero is determined on a base plate during assembly, a transformation matrix can be formulated from the coordinates of the part zero, the angle, and the axis of rotation angle. Any cutter paths generated in the part coordinate can be transformed into the machine coordinate, and NC codes for each cutter path can be generated.

$$\mathbf{P}_m = \mathbf{H} \times \mathbf{P}_p$$

where **H** is a homogeneous transformation matrix, and $\mathbf{P}_m = (x, y, z)_m$ and $\mathbf{P}_p = (x, y, z)_p$ are coordinates of cutter paths in the machine and the part coordinate, respectively.

In a fixture plan with clamps, when a part is placed on a horizontal base plate, the system assumes that a horizontal plate is positioned in the center of the workspace of the cutting machine tool and that the part/fixture assembly is situated at the center of the base. When a cutter path interferes with a base, the part should be raised from the base rather than allowed to overhang the base. When a part needs to be oriented on a sine table or an angle plate and can have direct contact with the base plate, the part is placed near the lifted end of the base plate so that features can be cut without interference between the cutter path and the base plate. However, when the part needs to be raised from a base plate due to clampable height, the part is placed so that it does not overhang the base plate. The location of the part zero is partially determined by the system and completed by a human expert in consideration of the size of the base (se Figure 4-14.)

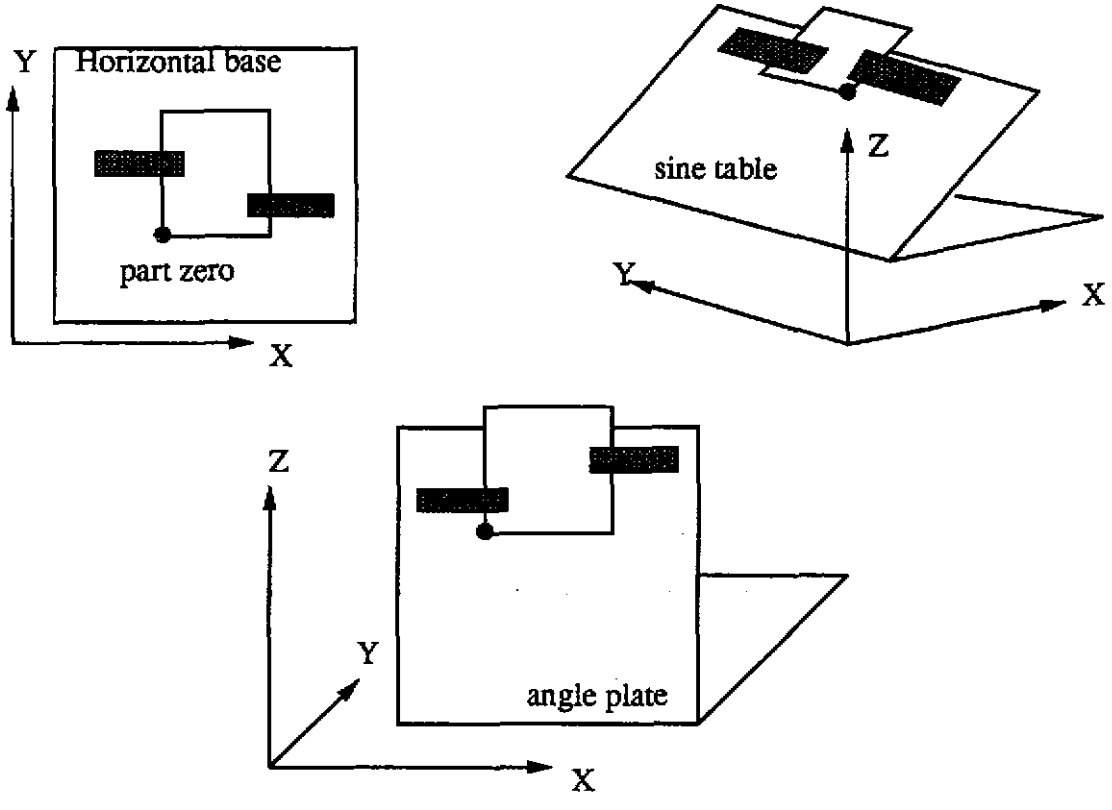


Figure 4-14: Part/fixture assembly of a fixture plan with clamps on various base plates

In a fixture plan with a vise, when a part needs to be placed on a horizontal base, both jaws are supposed to be installed such that a part and the vise is situated in the middle of the base plate. If a cutter path interferes with the base plate or the part needs to be exposed out of the vise for better access to the cutters, the part needs to be raised from the base by parallel bars. Both vise jaws need to be installed within a base plate when a part needs to be placed on a sine table or angle plate.

While the z coordinate of the part zero in the machine coordinate is determined by geometric reasoning implemented in the system, the x and y coordinates of the part zero in the machine coordinate need to be determined by a human expert. Figure 4-15 shows how the part in a fixture plan with clamps or a vise is positioned on various base plates.

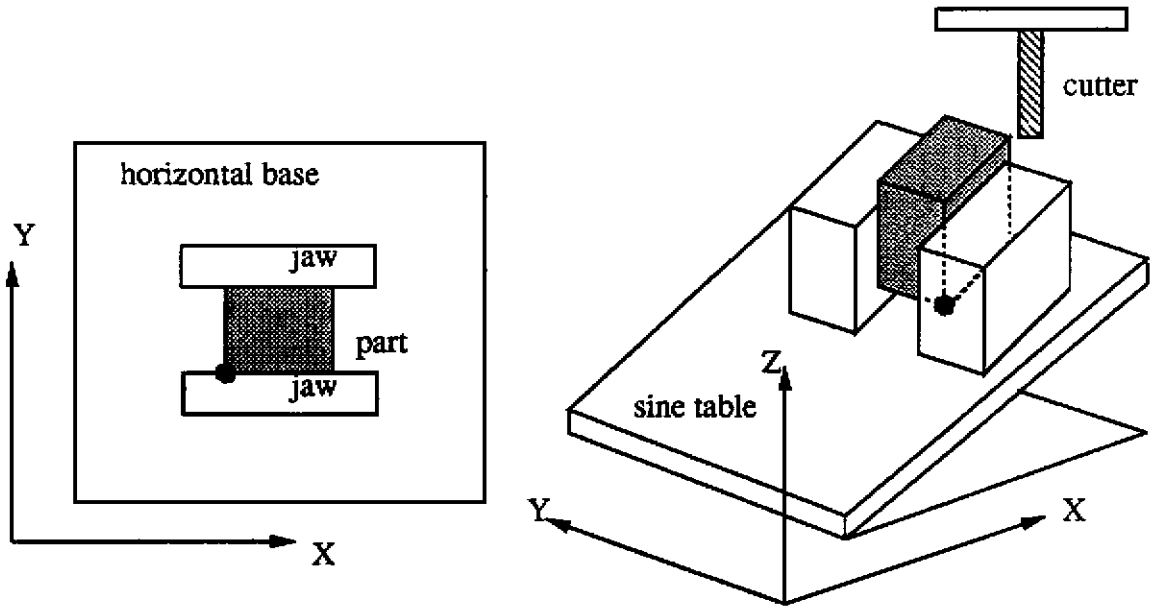


Figure 4-15: Part/fixture assembly on various base plates

4.8. Remarks

The proposed system can be used as an expert module to provide a human expert with fast answers about the existence of possible fixture plans for a given setup. Although a fixture plan with a vise is typically preferred due to its economy, a fixture plan with overhead clamps may be more cost-effective than the fixture plan with a vise.

The system has been developed with a 3 axis vertical milling machine in mind. For a horizontal milling machine or 5-axis milling machine, fixture plans can be generated with minor changes to the heuristics used in the system.

The system assumes that the part has three mutually perpendicular reference surfaces in order to accurately locate the part by the 3-2-1 rule. Reference surfaces may not be specified when the setup is to establish reference sides in a rectangular part. In this case, a setup planner can specify the sides for vise jaws as alternatives [Hayes 87] [Hayes 91].

If the part's location is identified in a setup and can be restrained in a known position, there is no need to locate the part in a subsequent setup(s). For example, in a fixture plan with clamps, the part's location from the previous setup can be maintained without moving the part while the location of clamps are changed. Also, the part's location can be fixed using locating pins inserted into holes or bolted down to a fixed location using through-holes.

T slots or pin holes on a base plate usually allow fixture components to be installed at the desired location on the base plate with the specified orientation. Because strap clamps have adjustable clamp bars and swing clamps are flexible in orientation, it is assumed that the clamp's location and orientation specified by the algorithm can be achieved with only a small discrepancy. If the modular fixturing system is not flexible enough to install fixture components at the specified location and orientation, the algorithm should consider the physical limitations in generating candidate fixture locations.

Although simplified fixture geometry is used for faster analysis and graphic displays, the detailed geometry of fixture components (such as clamps) can be used when displaying a simulated part/fixture assembly. In this case, additional parameters should be used to describe the clamp geometry.

When fixture plans have the problem of part deflection, it could take some time for a human expert to search and select the most favorable plan. If every plan is subject to deflection and cannot be prevented by supports, a setup planner should reduce the cutting force that is responsible for part deflection or abolish the setup. With the reduced cutting force, the system would generate fixture plans with fewer clamps and/or less clamping force. However, the reduction of cutting force can be achieved by reducing the the depth of cut and/or feed rate. However, this will result in longer machining time.

Regardless of fixture plans, when the problem of part deflection in a setup exists due to the cutting force a setup planner often may prevent part deflection by changing the order of the features [Englert 87].

The system may not generate any fixture plans at all. This happens either when cutting force is too large for the fixture components to apply enough clamping force to hold the part, or places for fixture components cannot be found around the part due to interference with cutter paths. In most cases, it is difficult to clearly pinpoint the reason. A setup planner could either reduce the number of features in a setup and/or reduce the cutting force.

The locations of fixture components in a fixture plan are specified in the part coordinate. Once the fixture plan is selected, the location of the part zero in the machine coordinate is determined by a human expert so that the part/fixture assembly can be situated properly on a base plate. Regardless of the location of the part zero in the machine coordinate, the assembly of each component should be done according to the location specified in the part coordinate. Cutter paths are also given in the part coordinate. A proper transformation matrix can be used to transform coordinates of cutter paths into the machine coordinate so that NC codes can be generated.

Although the system generates cost efficient plans, a human expert still plays a critical role in detecting part deflection and preventing it by taking appropriate actions for some setups. In order to further reduce human intervention, it is necessary to develop an intelligent scheme that can automatically detect unacceptable part deflection in a fixture plan with the aid of the finite element method(FEM). This issue will be pursued in our ongoing research.

Chapter 5
Fixture Planning with Clamps

5.1. Introduction

An overhead clamp applies force perpendicular to the part and is effective to hold the part rigidly. Because the overhead clamp bar is placed on the part, they have a tendency to limit the tool access to the part. Thus, the challenge for a tool designer is to generate a fixture plan in which the part can be held rigidly with the minimum number of clamps without deforming/deflecting the part and interfering with cutter paths.

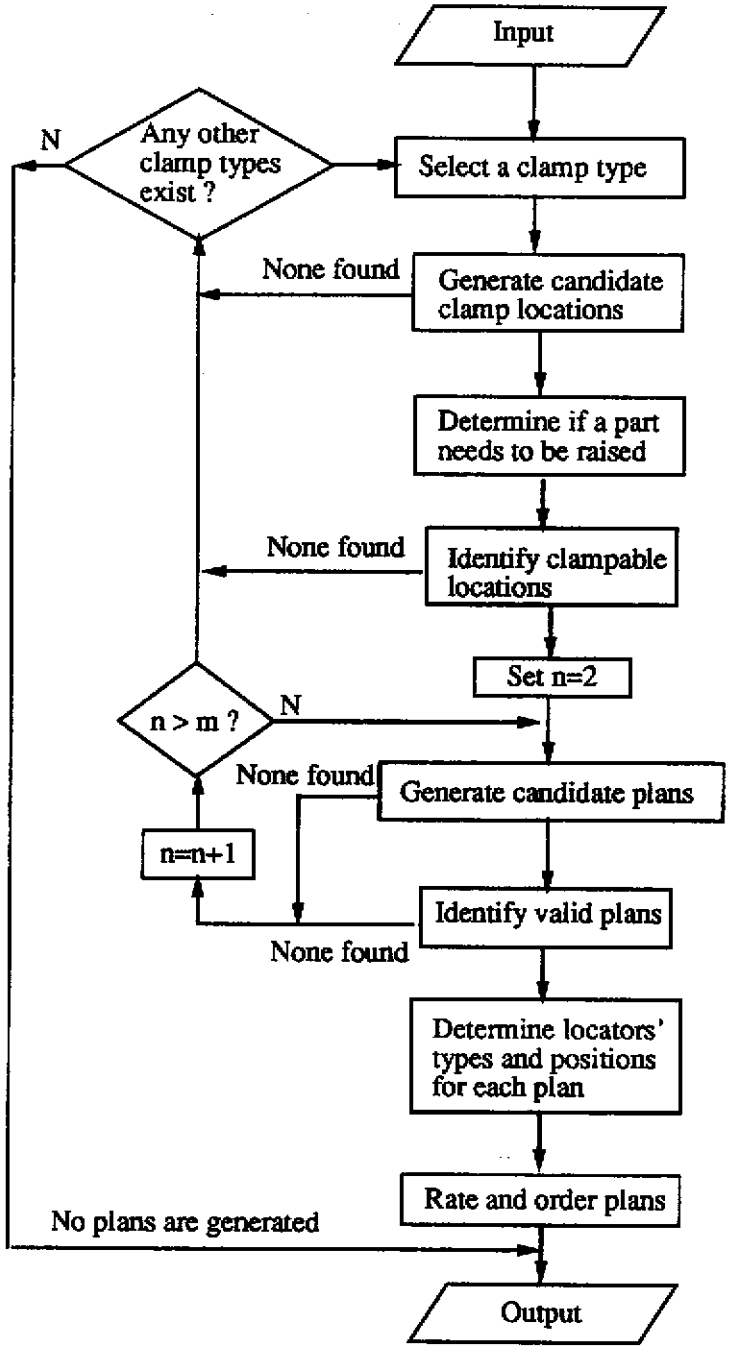
In this chapter, we describe an algorithm to automatically generate fixture plans with a minimal number of overhead clamps. Section 2 discusses assumptions made in the algorithm to generate practical fixture plans with clamps. Section 3 gives a flow diagram of the algorithm and describes the general methodology of the algorithm. Sections 4 through 10 discuss reasoning and mathematical tools used in each step. Section 11 concludes this chapter with remarks.

5.2. Overview of Algorithm

In order to satisfy the fixture requirements for a fixture plan with overhead clamps, the proper types, numbers, and locations of the locators, clamps, and supports must be determined in consideration of part geometry, fixture library, and cutter paths.

One of the important fixture requirements is that a fixture plan should be inexpensive and fast to assemble. Clamping during the fixture assembly typically requires much time and cost compared to locating or supporting. The fixture assembly time often proportionally increases with the number of clamps used in a fixture plan. Thus, a fixture plan with the minimum number of clamps is preferred as long as it satisfies all other fixture requirements. The use of a minimum number of clamps not only reduces assembly time and human intervention, but also often enables a setup planner to generate an economic setup sequence with the minimum number of setup plans by allowing cutters greater access to the part.

We have developed an algorithm that can automatically generate fixture plans with a minimum number of overhead clamps (see Figure 5-1). Fixturing principles, geometric reasoning, and common heuristics and practices used by experienced tool engineers have been incorporated into the algorithm to quickly generate practical fixture plans.



n = no. of clamps in a fixture plan
m = no. of clamps in the fixture library

Figure 5-1: Algorithm for automated fixture planning with overhead clamps

Because the goal is to generate fixture plans using the minimum number of clamps, a clamp type with the larger clamping force is favored over the other clamps. With the selected clamp type, the algorithm first generates every candidate clamp location on the part surfaces and then identifies valid clamp locations considering fixture requirements for clamping.

The algorithm exhaustively generates every candidate clamping plan by assigning a minimum number of clamps on the clampable locations and identifies valid clamping plans in consideration of the fixture requirements. If no valid clamping plans are found, the algorithm increases the number of clamps and generates a new set of candidate clamping plans. This process continues until at least one valid clamping plan is generated or the number of clamps exceeds the available number of clamps in the clamp data base. If no valid clamping plans are found even with the maximum number of clamps of the clamp type, another clamp type is selected. The same procedure is repeated until valid clamping plans are found or every clamp type in the clamp date base is tried.

For each valid clamping plan, the algorithm determines the positions of the locators according to the 3-2-1 locating rule and selects their types from the locator data base while considering relevant fixturing requirements. Decisions on whether the part needs to be raised from the base plate are made by considering cutter paths and clamp's physical limitation. When the part is raised from the base plate, a proper support is selected from the support data base and placed underneath each clamp if the part geometry permits.

When more than one fixture plan exists, the plan with a smaller clamping force is favored because the danger of part deflection due to clamping force would be reduced, and there is a larger safety margin between the required clamping force and the maximal clamping force of the clamp type. Thus, the algorithm rates highly the fixture plans with less clamping force and orders them so that a human expert may view the most highly rated plan first.

Several important steps in the algorithm are described in detail in the next few sections. These steps explain heuristics and/or geometric reasoning used to generate practical fixture plans along with the schemes used to speed up the computation.

5.3. Selecting a Clamp Type

There may exist multiple clamp types in the modular library. Various types of overhead clamps may exist in the library. A human expert may specify a clamp type, either a strap clamp or a swing clamp, considering part geometry and cutting operations. Otherwise, either clamp type will be used. Because the goal is to generate fixture plans using the minimum number of clamps, the algorithm selects a clamp type with the larger clamping force from the clamp data base.

Although it is possible to use more than one clamp type for a plan, it is assumed that the same clamp type is used in the fixture plan in order to reduce the search space according to the practice.

5.4. Generation of Candidate Clamp Locations

5.4.1. Identifying Clampable Surfaces

Because an overhead clamp can only apply force perpendicular to the base plate, the clamp should be placed on part faces parallel or near parallel with the base plate. Thus, part faces with a unit normal equal to or close to (0,0,1) in the part coordinate are candidate faces on which an overhead clamp can be placed. From now on, we will refer to these candidate faces as *clampable part faces*. Some parts may not have clampable part faces, and fixture plans with overhead clamps are not possible.

5.4.2. Edges as Candidate Clamp Locations

The part's geometry is described by a boundary representation with the assumption of "winged edges". In our system, the part geometry is constructed so that each edge of a clampable part face is always shared by another face which has a different unit face normal.

Although the entire area of a clampable part face is used for clamp locations, the possibility would be infinite. A clamp should not interfere with the part while providing the cutter with good access to the part. Clamp locations are found near the boundary of clampable part faces in order to satisfy both constraints. In the algorithm, every edge of clampable part faces is considered as candidate clamp locations. Note that boundary representation of the part geometry represents a curvilinear surface by many discreet facets. As a result, a clampable part face may have many short edges when its edges share curvilinear surfaces.

In order to reduce the search space, the following geometric reasoning is used considering the limitation of clamp's geometry for each edge. If the z coordinate of the edge of a clampable face is the same as another face's minimum z coordinate, the edge cannot be used for clamp locations because the clamp will interfere with the part geometry. Figure 5-2 shows accessible and inaccessible edges of an overhead clamp in consideration of part geometry. When a clampable part face lies within a hole, a clamp cannot be placed on the face because every edge is inaccessible due to interference between the clamp and the part.

5.4.3. Discretization of Edges

There are virtually an infinite number of ways to place a clamp over an accessible edge. In order to make the solution space finite, each accessible edge is discretized into points by a spacing.

The algorithm exhaustively generates clamping plans by assigning clamp locations for the specified number of clamps in a clamping plan. Typically, the number of candidate fixture plans increases with the number of candidate clamp locations. Thus, it is important to choose an appropriate spacing for discretization. With a large spacing, the number of candidate clamp locations would be small. However, there is a danger that the algorithm may not generate any fixture plans due to a small search space. With a small spacing, many candidate fixture plans would be generated, and it would be time-consuming for the

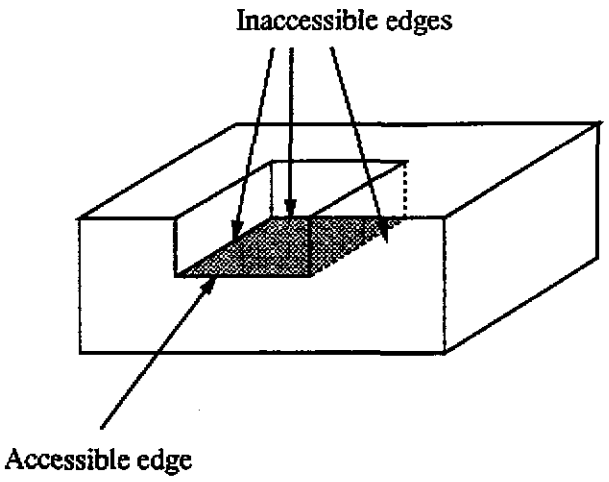


Figure 5-2: Accessible and inaccessible edges of a clampable part face

algorithm to check fixture requirements in each plan. Also, it would take more time for the human expert to check part deflection and select a favorable plan. Thus, the algorithm heuristically determines a reasonable spacing according to the part size.

The heuristics to discretize each edge into finite clamp locations are as follows. Let L be the length of an edge of a clampable part face and S be the spacing. If $L \leq 2\ S$, a midpoint of the edge is used for a clamp location. If $L > 2\ S$, the edge is discretized into more than one clamp location by S. Currently, S is set to be 0.3".

The clamping location is determined so that the desirable contact area of the clamp does not overhang the edge of the clampable part face (see Figure 5-3). Each clamp location is the position of a clamp's origin in the part coordinate. Each candidate clamp point is described by the x, y, and z coordinates for the clamp's origin in the part coordinate and the orientation angle about the Z axis of the part coordinate.

5.4.4. Orientation of Clamps

An overhead clamp should be placed on the part so that its main body does not interfere with the part, which will provide cutters better access to the part. In practice, the clamp bar is often oriented perpendicular to the edge of the part at the clamp location unless it is not possible due to other constraints (see Figure 5-4).

When the part is oriented by a sine plate or an angle plate, the part overhangs the base plate to avoid interference between the base plate and the cutter paths. Thus, a clamp cannot be placed over an edge unless its orientation allows the clamps to be situated within the base plate (see Figure 5-5). The current heuristics orients the clamp either parallel to the Y axis (or X axis) of the part coordinate when the part orientation is about the Y axis (X axis).

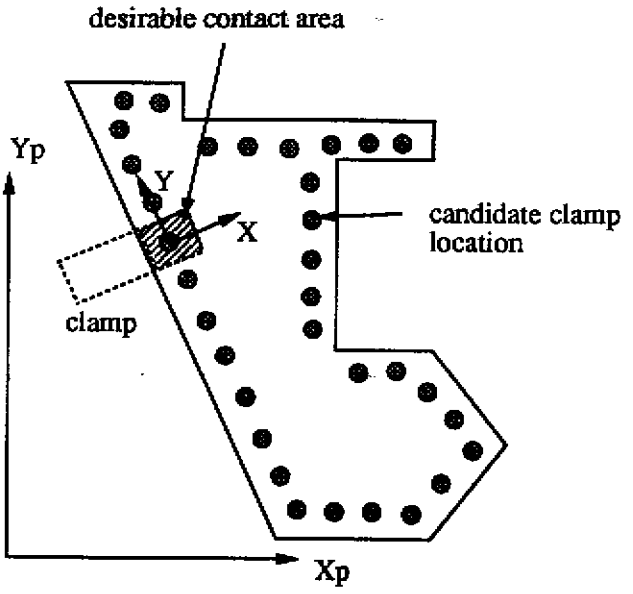


Figure 5-3: Candidate clamp locations on a clampable part face

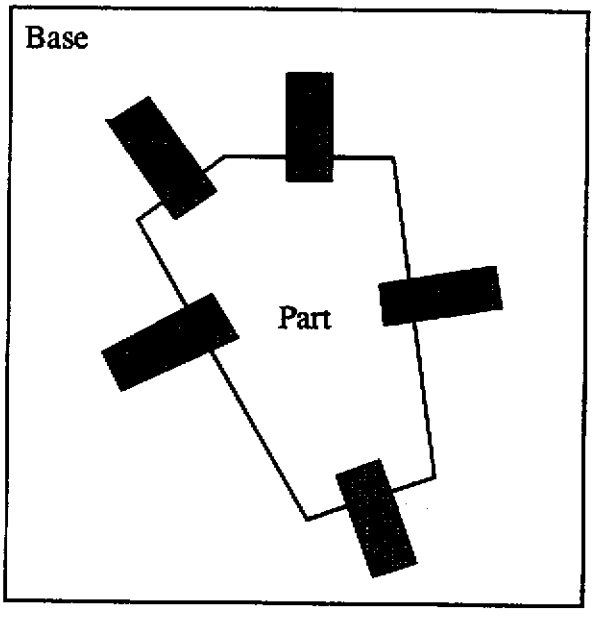


Figure 5-4: Orientation of clamps

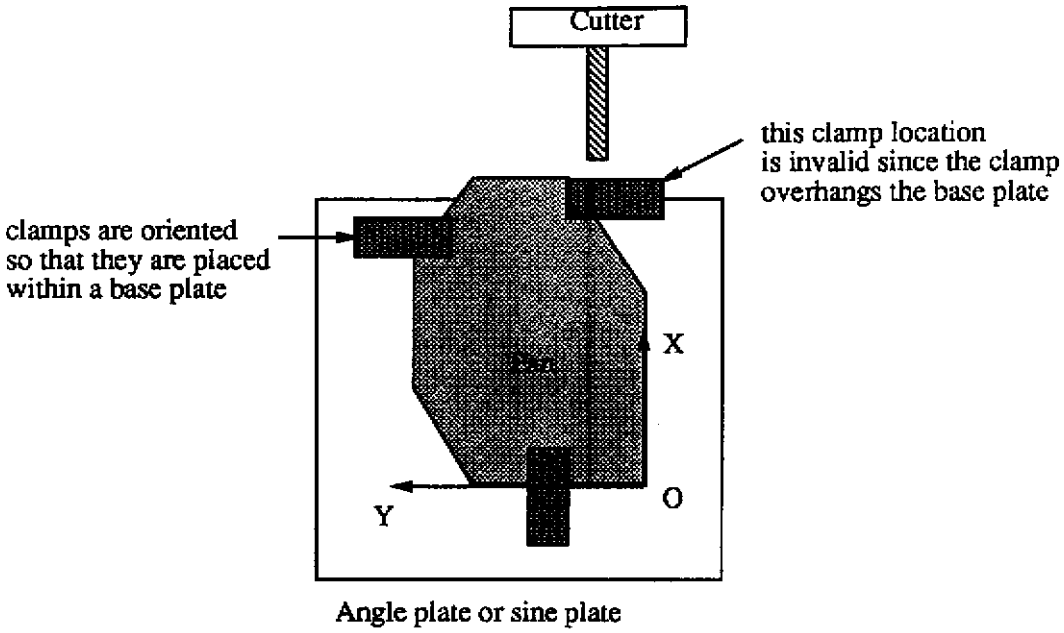


Figure 5-5: Clamp orientations adjusted considering the physical limitation on a sine or angle plate

5.5. Supporting with a Base plate or Supports

The part can be supported by a base plate, supports, or a subplate. Supporting by the base plate is usually preferred because it not only provides better locating and supporting than supports or a subplate, but also takes less assembly time. In this algorithm, we have generated plans both with and without supports.

5.5.1. Raising the Part from a Base plate

There are two cases where the part needs to be raised from the base plate: 1) when any cutter path interferes with the horizontal base plate and 2) when the clamp's minimum clampable height is higher than the maximal z coordinate of every clampable location.

Case 1: **when any cutter path interferes with the horizontal base plate**

When a horizontal plate is used to orient the part, it is assumed that the part/fixture should be situated in the center of the horizontal plate. Thus, when a cutter path interferes with the horizontal plate or is too close to the horizontal plate, the part needs to be raised. For example, a cutter path for drilling operations to make through-holes would interfere with the base plate unless the part is raised. The same is true for a cutter path for end milling operations to cut part sides Currently, when the lowest z coordinate of a cutter swept volume in the part coordinate is lower than some clearance (for example, 0.2") from the base, the part is raised.

When a sine table or an angle plate is used to orient the part, the part can overhang the base without being

raised from the base. The part needs to be placed such that any cutter path does not interfere with the base plate. The location of the part zero on a sine table or an angle plate is determined by applying the interference checking algorithm between the cutter paths and the base plate as shown in Figure 5-6.

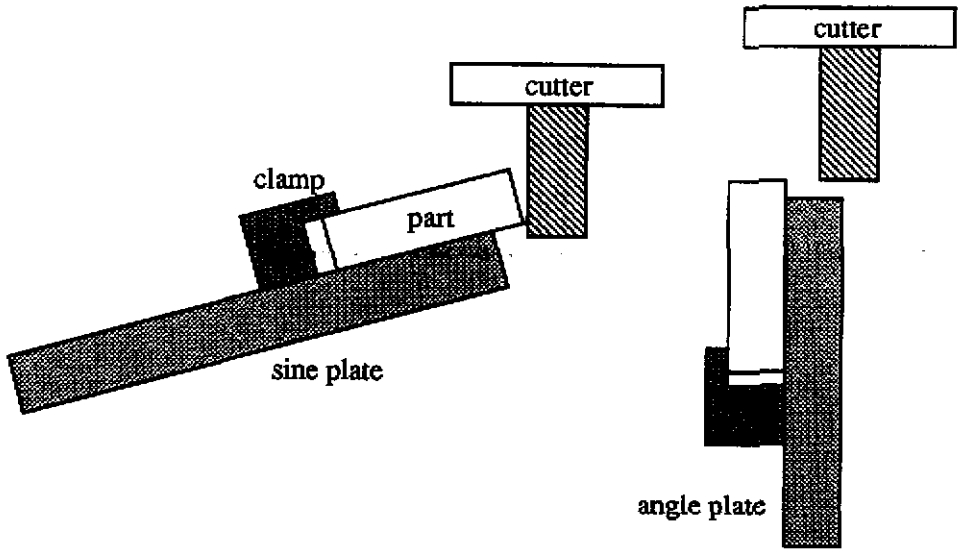


Figure 5-6: Part location on a sine table or an angle plate

Case 2: when the clamp's minimum clampable height is higher than the maximum height of the clamp locations on the part

If the clamp locations' maximal z coordinate is shorter than the minimum clampable height of the clamp, the part cannot be clamped unless it is raised (see Figure 5-7).

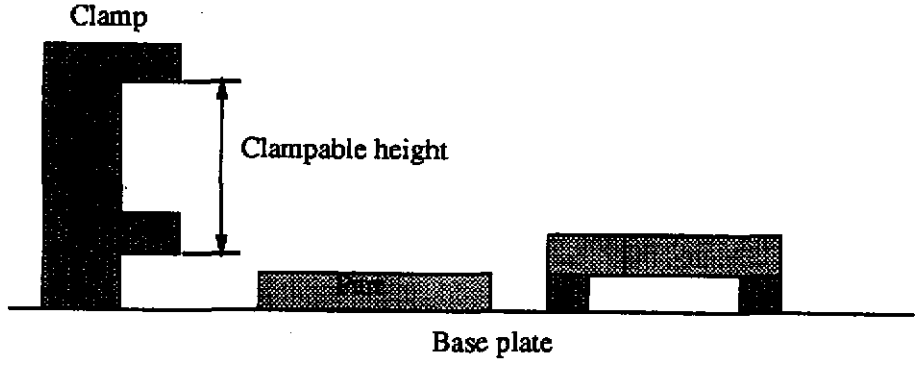


Figure 5-7: Two cases where a part needs to be raised

5.5.2. Determining the Height of Supports

When the part is supported by the base plate and a few valid clamp locations exist, no valid clamping plans may be found if every candidate clamping plan violates the fixture requirements. By raising the part from the base plate, new clamp locations may be identified and valid clamping plans may be generated (see Figure 5-8). On clampable part faces at the lower height, extra clamp locations are found, and

unacceptable part deflection due to clamps does not exist because a support can be placed under each clamp.

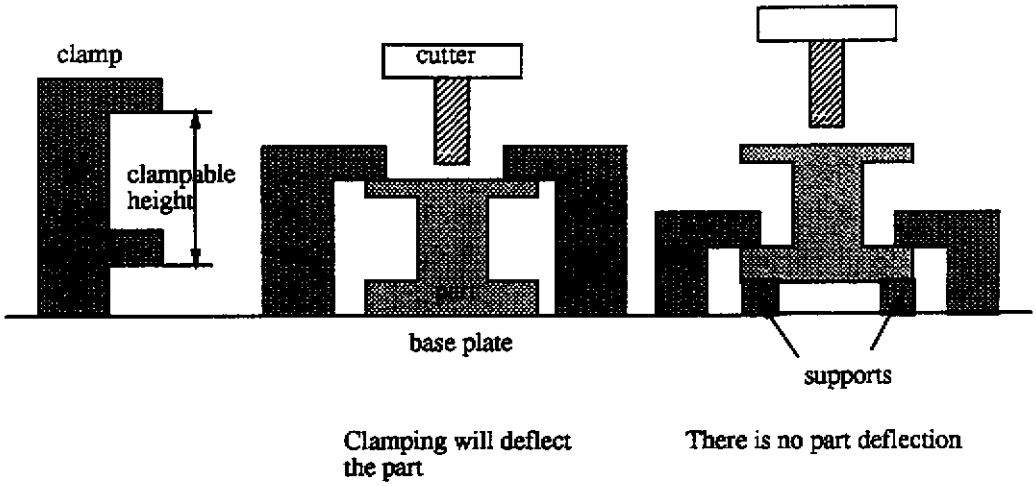


Figure 5-8: Fixture plans generated for an I-shape part

When generating fixture plans with the part raised from the base plate, supports or a subplate should contact the part's bottom reference surfaces in order to provide accurate locating. The height of supports is determined so that the shortest height of clamp location(s) becomes higher than the clamp's minimum clampable height when the part is raised. Let z_{min} be the lowest z coordinate of the lowest clamp location, H_{clamp} be the minimum clampable height, and $H_{support}$ be the support's height. Then the part is raised by the available supporting components with the minimum height in the fixture library so that $z_{min} + H_{support} \geq H_{clamp}$. The algorithm selects appropriate supports from the support data base and places them underneath each clamp location if the part geometry permits.

5.6. Identification of Valid Clamp Locations

Clamp locations become invalid if they violate any fixture requirements. For a candidate clamp location to be valid, the following requirements should be satisfied.

- A clamp should be placed within the base plate that supports the part.
- There should be no interference between the clamp and the part.
- There should be no interference between the clamp and cutter paths.
- The clamp should not cause the part to rotate during assembly.
- The z coordinate of the clamp location should be within the minimum and maximum clampable height of a clamp.

In order to speed up the computation, the clamp geometry is modeled as an L-shape polyhedron in the algorithm while preserving the critical dimension of the clamp. However, a clamp can be modeled as another polyhedron with more faces, if the L-shape polyhedron does not represent the clamp adequately.

In order to check if a candidate clamp location satisfies fixture requirements, each clamp's geometry is

constructed in the part coordinate according to the position and orientation of the candidate clamp location. Note that interference between a clamp and locating elements is not considered at this stage since the algorithm determines the locators' positions and types only after valid clamping plans are generated.

5.6.1. Physical Limitation

If the clamp lies outside or overhangs the base plate, the clamp location is not valid. In the current system, we have assumed that the size of a base plate is big enough to have the part/fixture assembly within the base plate. However, if the clamp overhangs the plate as shown in Figure 5-5, the clamp location becomes invalid.

5.6.2. Interference checking between a clamp and cutter paths

In Chapter 4, the construction of the swept volume of a cutter path has been discussed. The swept volume of a straight cutter path is modeled by a rectangular box. The swept volume of a circular cutter path is conservatively approximated by a few straight cutter paths and then each discrete path is modeled by a rectangular box.

A clamp needs to be some distance away from the swept volumes of cutter paths in order to provide safety and allow some flexibility in fixture location and orientation during the actual assembly. The dimension of the clamp geometry is enlarged to consider some clearance between the clamp geometry and the cutter paths. Figure 5-9 shows the enlarged geometry of a clamp with added clearance. If the enlarged clamp geometry interferes with any swept volume, the clamp is considered to be interfering with the cutter path.

Because the 3D interference checking algorithm is computationally expensive, it is used only when there is a possibility of interference. A comparison between minimal and maximal x, y, and z coordinates of the locator and the swept volume can quickly detect the possibility of interference. For example, when a swept volume's minimal z coordinate is above the clamp' geometry's maximal z coordinate, there is no interference between the clamp and the swept volume.

When the possibility of interference between a clamp and a swept volume is not excluded by the fast geometric checking described in Chapter 3, every combination between the face of two objects should be tried iteratively until an interference is detected. Because the computational time of the interference checking algorithm increases proportional to the number of faces of objects, it is desirable to speed up the computation.

When a horizontal plate or an angle plate is used to orient the part, the interference checking between the geometry of a clamp and a swept volume can be done in 2D because the swept volume is oriented parallel to the base plate. The swept volume and the clamp's geometry is simplified by a rectangular face that is parallel with the base plate in the plane. (see Figure 5-10) As a result, the number of iterations required to detect interference between a clamp and a swept volume is reduced from 48 (8 faces on a clamp and 6 faces on a swept volume) to 1.

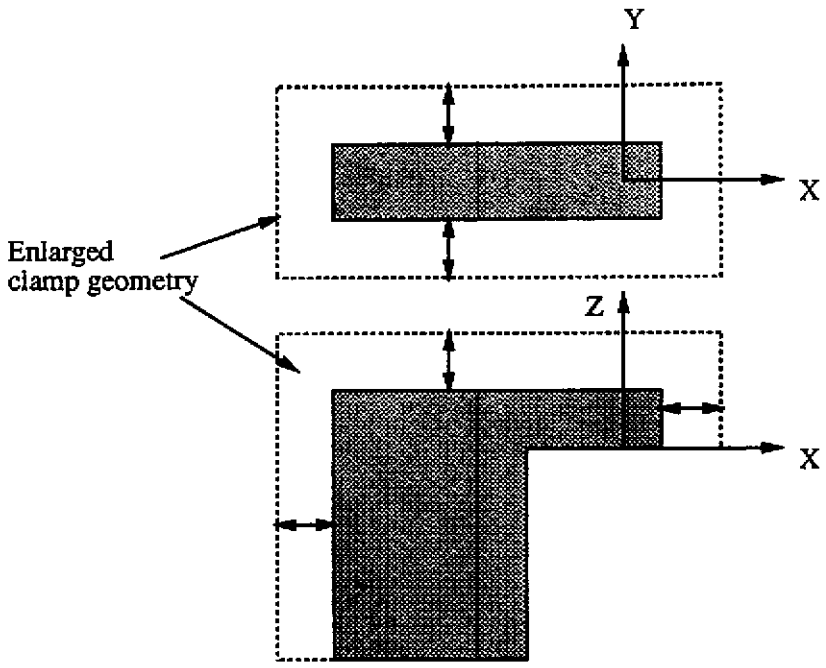


Figure 5-9: Enlarged clamp geometry with added clearance

When a sine table is used to orient the part relative to the machine bed, 2D interference checking is not possible. For each set of faces of the clamp and the swept volume, the minimal and maximal x, y, and z coordinates are compared to detect the possibility of interference before using the 3D interference checking algorithm.

5.6.3. Interference checking between a clamp and the part

When a clamp is placed at a candidate clamp location, it should not interfere with the part To allow clearance between the clamp and part during assembly, the enlarged clamp geometry is used for interference checking between the clamp and part, similar to the clamp geometry as shown in Figure 5-9.

To speed up the computation in the interference checking algorithm, only critical faces of a clamp and faces of the part are considered. On a clamp, side faces of the clamp geometry are sufficient for interference checking because top and bottom faces are redundant.

Many faces in the part can be ignored in the intersection checking if they cannot interfere with the clamp geometry at all. Let z_{max} be the maximal z coordinate of a part face and z_c be the z coordinate of a candidate clamp location. The following heuristics are used to ignore part faces for interference checking.

- A face that a clamp bar is placed against.
- Faces whose face normal is parallel with the base and whose $z_{max} \leq z_c$
- Faces within a hole where there is no accessible part face for clamp locations.

Note that the heuristics only include unnecessary part faces that can be quickly identified. More part

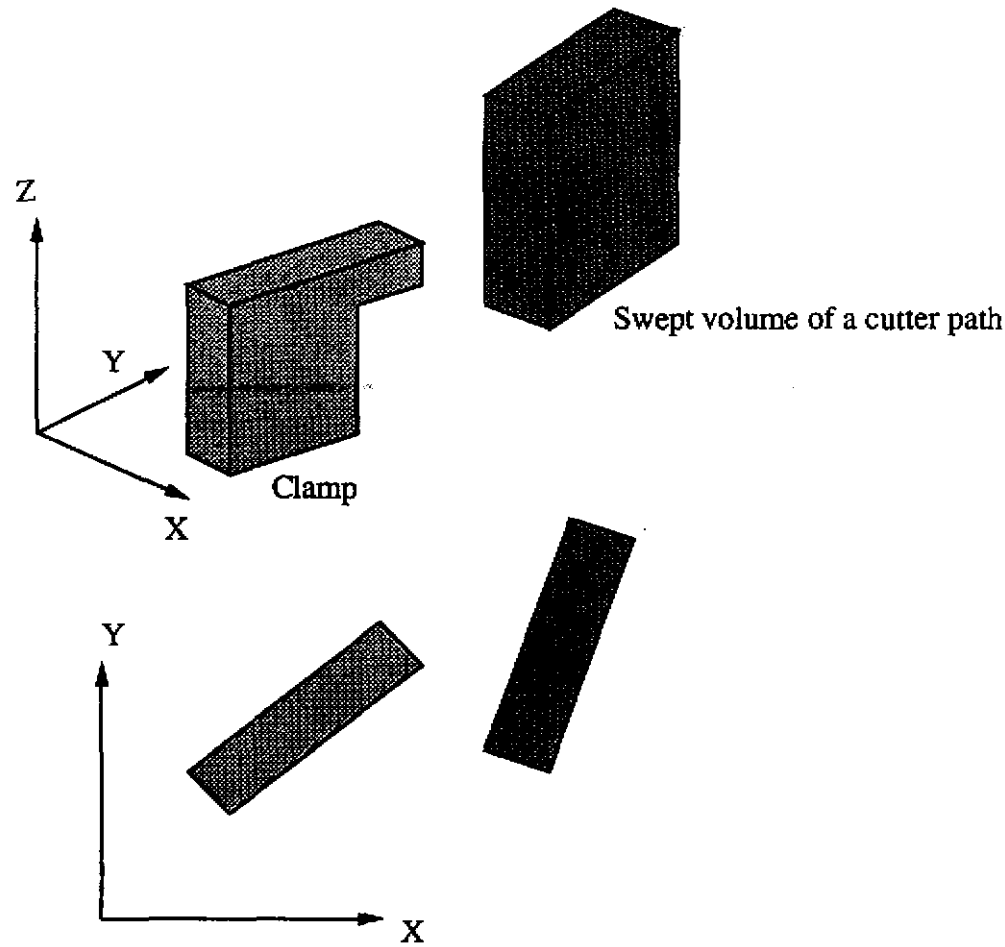


Figure 5-10: 2D interference checking between a clamp and a swept volume

faces could be ignored if more sophisticated geometric reasoning is used. Figure 5-11 shows part faces that are used for interference checking against a clamp. With the heuristics, only a few faces of the part are used for interference checking, and the computation time is greatly reduced. In order to further speed up the interference checking, the minimal and maximal x, y, and z coordinates of faces of part and clamp geometry can be compared to detect the possibility of interference before using the 3D interference checking algorithm.

If the clamp geometry interferes with the part and the clamp type is a strap clamp with a adjustable clamp bar, the algorithm checks to see if the clamp geometry with extended clamp bar also interferes with the part (see Figure 5-12). The clamp bar's extended length is conservatively determined to avoid any deflection in the clamp, in case the clamp applies the maximum clamping force. If the clamp and the part still interfere, the clamp location is not valid. This consideration can be ignored if valid clamp locations need to be identified conservatively.

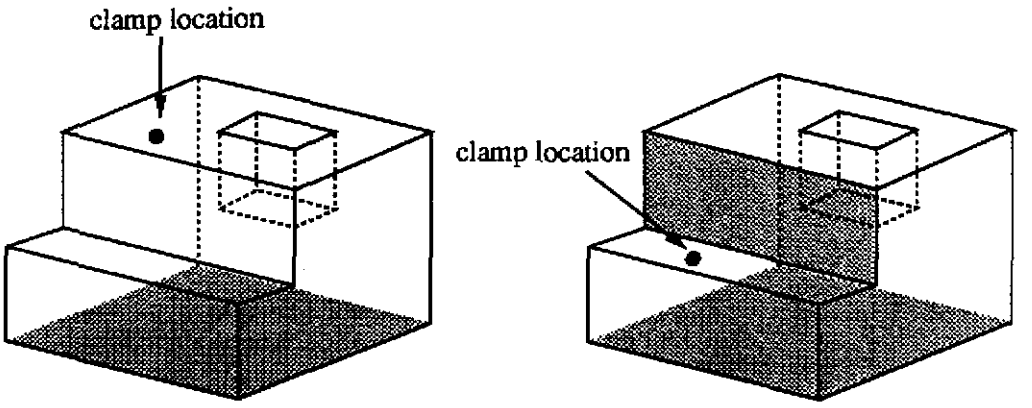


Figure 5-11: Part faces considered for interference checking between the part and the clamp geometry

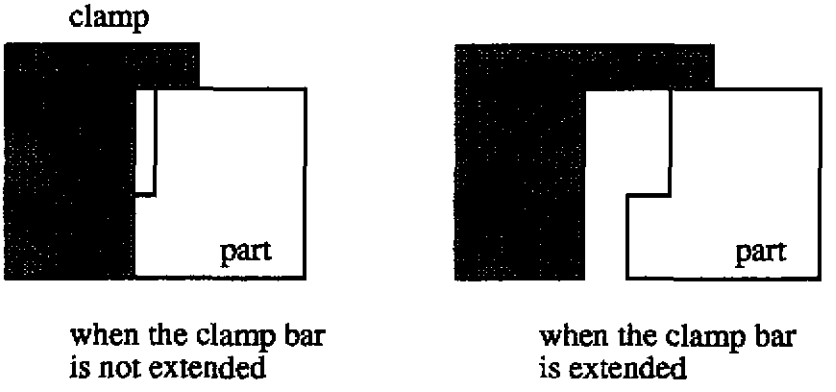


Figure 5-12: Extension of a clamp bar to avoid interference with the part

5.6.4. Part rotation checking

Since the algorithm only considers supporting elements that can be placed against the bottom reference surface of the part, supports cannot be placed to prevent rotation due to the clamping force when a clamp is over the concavity. Thus when a support cannot be placed directly under the clamp, the clamp could cause the part to rotate during fixture assembly regardless of the assembly order. A mathematical tool that checks an invalid clamp location has been developed based on screw theory and is described in Chapter 3.

If a clamp could rotate the part, a new clamp location moved further inward from the edge can be tried (see Figure 5-13). The new clamp location also should be checked for interference against the part geometry and the cutter paths to be a valid clamp location. If the clamp and the part interfere and the clamp type is a strap clamp with an adjustable clamp bar, the clamp geometry with an extended clamp bar can be tried for interference against the part. Again, this consideration can be ignored if valid clamp locations need to be identified conservatively.

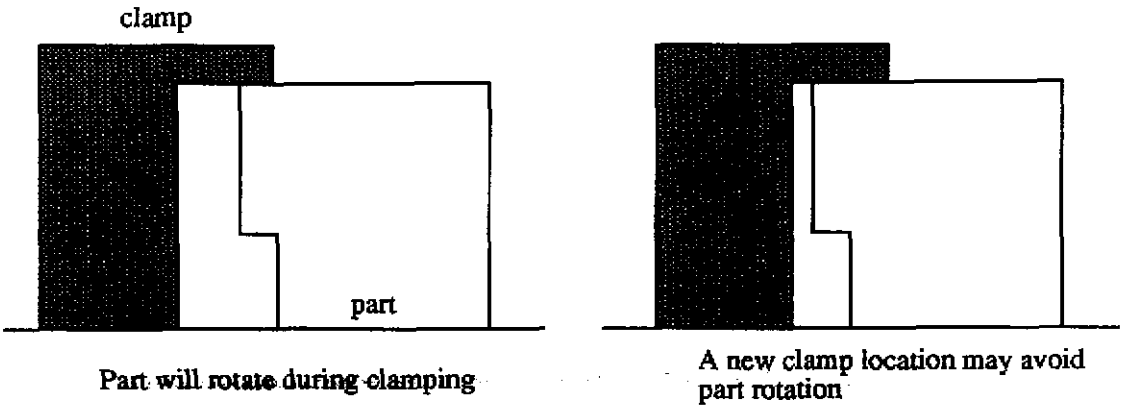


Figure 5-13: A new clamp location to avoid part rotation

5.6.5. Checking with Clampable Height

In order for a candidate clamp location to be valid, the height of the clamp location from the base plate should be within the minimum and maximum clampable height of the clamp type in consideration.

Although a candidate clamp location is valid when the part is supported by a base plate, it may become invalid when the part is raised by supports or vise versa.

5.6.6. Estimating Contact Area between Clamp and the Part

Depending on the contact area and clamping force, the part can be deformed at the clamping location if the stress exceeds the yield strength of the part material.

The desirable contact area of the strap clamp and the swing clamp is shown in Figure 5-14. The desirable contact area can be modeled as a rectangle for fast estimation. While a strap clamp type has a large contac area, a swing clamp type may have a small contact area. A function for interference checking in the NOODLES library [Gursoz 91] can be used to estimate the contact area between the clamp and the part at each clamp location.

5.7. Generation of candidate clamping plans

Each clamp location has information on the x, y, z coordinates, clamp orientation in the part coordinate and the clamp bar's extension, if the clamp type is a strap clamp. These clamp locations are used to generate various candidate clamping plans.

Because the fixture plan with the minimum number of clamps is preferred in order to minimize the assembly cost and time, the algorithm first generates various plans using the least number of clamps. A fixture plan with one clamp cannot maintain the moment equilibrium of the part at all because there is not enough frictional torque which resists the moment caused by the cutting forces. Thus the minimum number of clamps for a fixture plan should be 2.

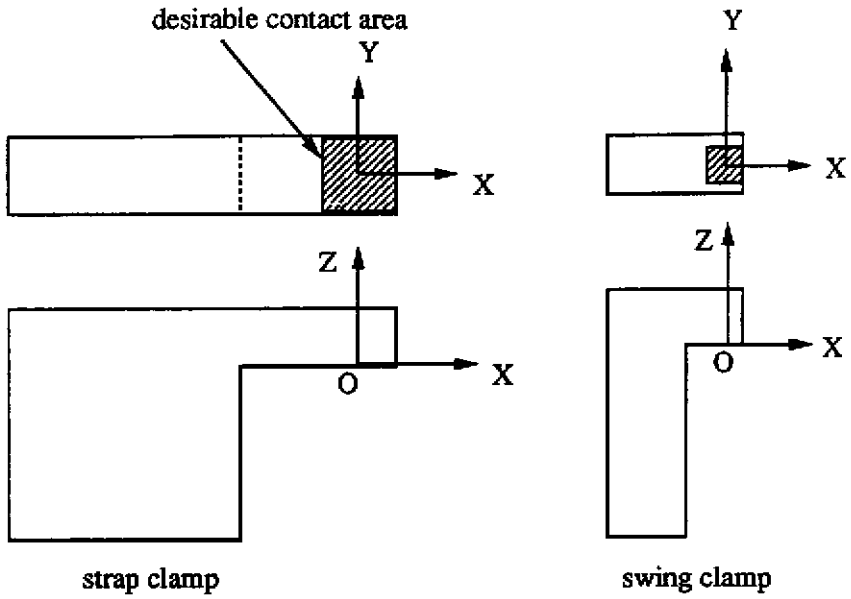


Figure 5-14: Desirable contact area of a clamp

Let m be the number of clamps and n be the number of clamp locations. The number of candidate clamping plans would be equal to the number of ways to choose m locations out of n locations without redundancy. Thus the number of candidate clamping plans with m clamps on n clamp locations can be expressed as

$$mCn = \frac{m!}{n!\,(m-n)!}$$

For example, if n=10, then the number of candidate plans is 45 with m=2, 120 with m=3, and 210 with m=4.

If the number of clamp locations is less than the number of clamps in a plan, no candidate plans exist. If candidate plans with the current number of clamps do not exist due to the lack of clamping force or part deformation, an increased number of clamps should be tried for a fixture plan. If every clamping plan becomes invalid due to the interference between clamps, another clamp type should be tried because every clamping plan with the increased number of clamps are always invalid due to interference.

5.8. Identification of valid plans

Although numerous candidate plans may exist when there are many clamp locations, many of them will be invalid if they violate fixture requirements. For a candidate clamping plan to be valid, 1) there should be no interference between clamps, 2) the magnitude of the estimated clamping force should be less than the maximum clamping force of a clamp, and 3) there should be no part deformation due to clamping force.

The estimation of clamping force is much more computationally expensive than the interference checking between clamps. If there are many candidate clamping plans, it could take some time to identify valid

plans. In order to reduce computation time, interference checking is done first. Part deformation checking is required only when the clamping plan passes the first two tests.

5.8.1. Interference between Clamps

If clamps in a candidate clamping plan interfere with each other, the plan is not valid. The algorithm exhaustively checks interference between every 2 clamps in a plan.

Since clamps should not interfere when projected onto the base plate, the interference checking between clamps can be done in the plane. Thus, the number of iterations required to check interference between clamps is reduced from 64 (8 faces for each clamp) to 1.

A clamp is placed within the part concavity when it is positioned over an edge within the concavity of a clampable face. Except when both clamps are placed within the part concavity, any interference can be quickly checked by computing the distance between the clamp locations because there is no possibility of interference between their clamp bodies. As discussed earlier, the clamp's contact area is modeled as a rectangle. For the simpler geometric reasoning, this rectangle can be bounded by a circle. Let its radius be R. Also, let the distance between two clamp locations be L, and the clearance between clamps for assembly be δ. Then, if $L < 2R + \delta$, clamps will interfere with each other, and the fixture plan should be discarded. If both clamps are placed within the part's concavity, interference checking algorithm should be applied.

Figure 5-15 shows the 2D representation of clamps in a candidate clamping plan. Interference between clamps A and C, A and D, and C and D are checked by the interference checking algorithm since both clamps are placed within the part's concavity. The rest of the clamp combinations can be checked by the distance between the clamp locations. Since clamps C and D are too closely placed, the clamp plan becomes invalid.

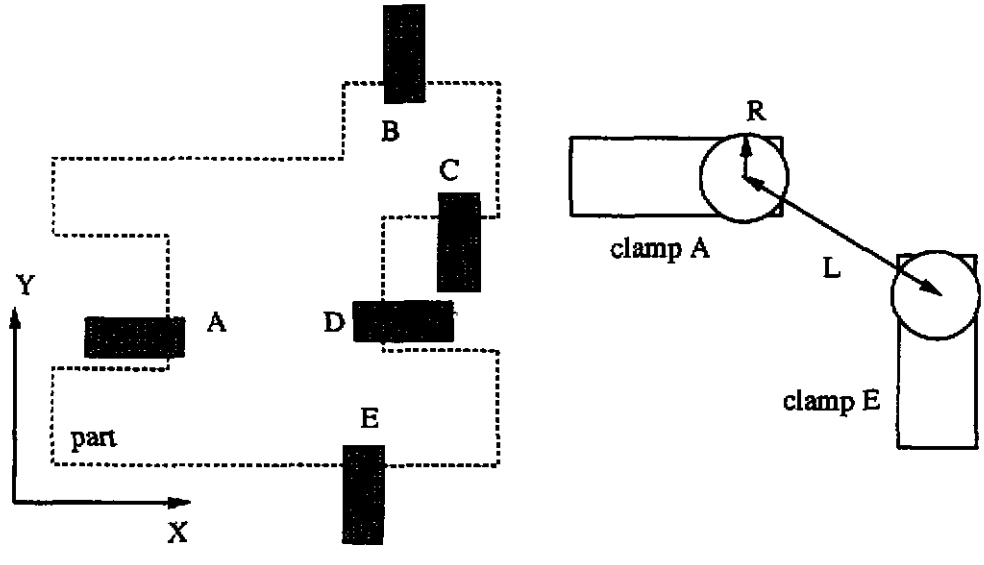


Figure 5-15: 2D interference checking between clamps

When every candidate plan generated with a given number of clamps is invalid due to interference between clamps, the algorithm immediately selects a clamp type with a smaller geometry and generates a new set of clamp locations since it is not feasible to generate interference-free plans with an increased number of the current clamp type.

5.8.2. Estimating Clamping Force

In a clamping plan, each clamp should be able to apply adequate force to hold the part rigidly during machining without deforming or deflecting the part. Thus, it is necessary to estimate the minimum clamping force considering the magnitude and direction of each cutter path.

Force analysis to compute a clamp force for a fixture plan has been described in Chapter 3. For each cutting direction, the minimum clamping force is estimated. If the estimated clamping force is beyond the clamp's maximum clamping force, the plan becomes invalid. The largest force among the minimum clamping forces estimated for each cutting direction is the necessary clamping force to hold the part against any cutter paths during machining. Typically, when clamps are spread out in a plan, a smaller clamping force is required.

A mechanically driven clamp cannot accurately adjust to the specified magnitude of the clamping force. The hydraulic clamp can adjust its clamping force accurately. In practice, a tool designer would typically apply a larger magnitude of clamping force in order to ensure a rigid hold over the part.

5.8.3. Checking Part Deformation at clamp Locations

The clamp in a fixture plan may deform the part, depending on the contact area between the clamp and the part, part material, and clamping force. When the clamp is located over a narrow part face or a face with hole(s), the actual contact area between the clamp and the part may be smaller than the desirable contact area of the clamp (see Figure 5-16).

The stress at the clamp location is computed by dividing clamping force by the contact area estimated at each clamp location. If the stress at a clamp location is larger than the lower yield point of the part material, the clamp would deform the part, and the clamping plan becomes invalid.

For the strap clamp, the contact area is estimated by taking the intersection between its clamp bar's bottom surface and the part. For the swing clamp, the contact area is estimated by taking the intersection between its desirable contact area and the part. A mechanically driven clamp often may not apply the exact clamping force. In this case, a clamping force (often maximum clamping force) larger than the estimation should be used to estimate the stress at the clamp location for safety reasons. Because the swing clamp's desirable contact area is typically small, there is a greater danger of part deformation at the clamp location when the clamp applies a large clamping force.

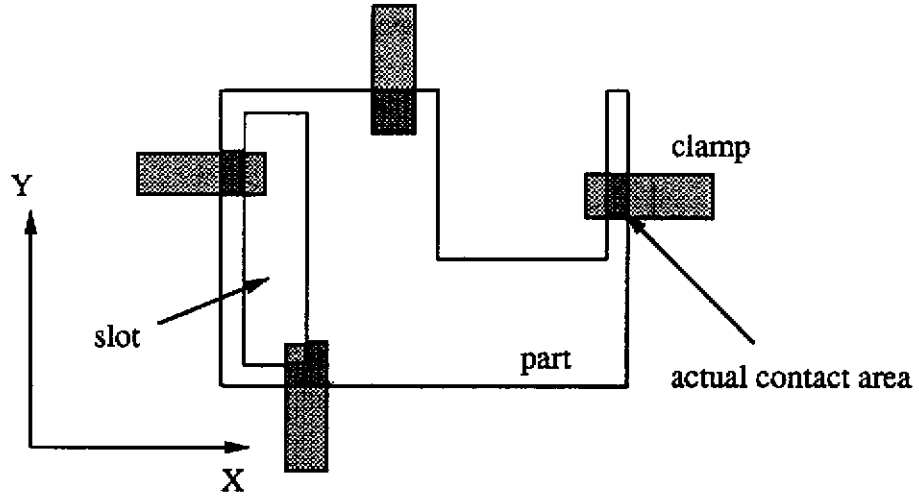


Figure 5-16: Contact area at a clamp location

5.9. Determination of Position and Height of Locators

So far, the algorithm has generated every possible clamping plan with the minimum number of clamps and determined supporting plan. In order to complete the fixture planning, the locating plan should be made for each fixture plan. Locating planning includes the determination of locators' positions and the selection of appropriate types from the locator data base. The following constraints should be considered during locating plan:

- Locators should be placed according to the 3-2-1 rule.
- A locator should have good contact with the part.
- A locator should not interfere with clamps.
- A locator should not interfere with cutter paths.

An algorithmic procedure has been developed to automatically determine the positions of locators and select the appropriate types from the locator's data base.

1. Generate possible locator positions by discretizing side reference surfaces with an appropriate spacing.
2. Select locator positions for a candidate locating plan.
3. At each position, select the locator with the minimum height from the locator data base considering contact with the part.
4. If any locator interferes with the clamps or cutter paths, return to Step 2.

If any locator position in a candidate locating plan violates fixture requirements, another set of positions is tried repeatedly until a valid set of locator positions is found.

5.9.1. Generation of Candidate Locator Positions

In the X-Y plane of the part coordinate, side reference surfaces are represented as lines along the X and Y axis. Each line is discretized with a spacing to generate candidate locator positions. If a base plate has pin holes, the spacing should be the distance between the holes. Figure 5-17 shows candidate locator positions along the side reference surfaces of the part.

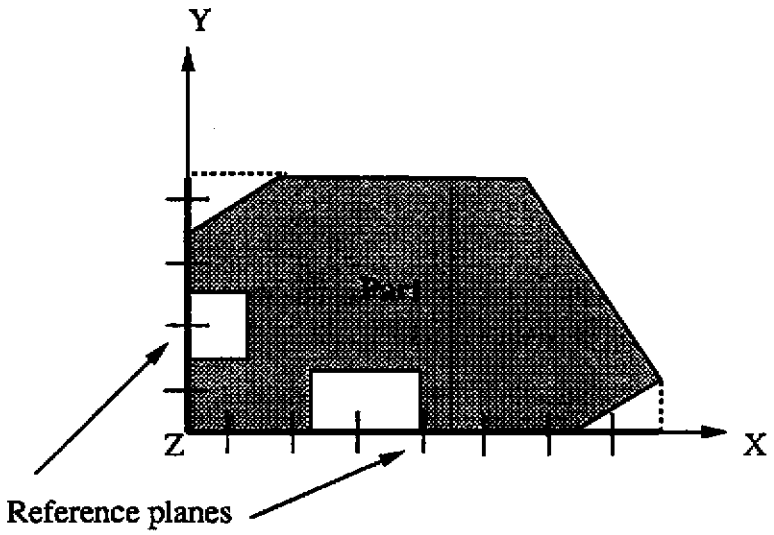


Figure 5-17: Candidate locator positions

5.9.2. Generating a Candidate Locating Plan

As discussed in Chapter 4, part locating in metal cutting is done according to the 3-2-1 rule. The 3-2-1 rule dictates that 3 point contacts, 2 point contacts, and 1 point contact should be placed against three mutually perpendicular reference surfaces of the part in order to accurately locate the part relative to the machine tool.

Three 3 point contacts on the bottom reference surface can be achieved either with a base plate or with 3 supports. The algorithm achieves 2 point contacts by placing two locators on a side reference surface and 1 point contact by placing one locator on another side reference surface. As shown in Figure 5-18, there are two possible ways to place locators along side reference surfaces of the part - 1) 2 locators against the X-Z datum plane and 1 locator against the Y-Z datum plane and 2) 2 locators against the Y-Z datum plane and 1 locator against the X-Z datum plane. Arrows indicate the search direction for subsequent candidate positions of locators when the current position cannot be used.

According to the locating principle in practice, locators' positions are selected as far apart from each other as possible to provide better accuracy in part locating. The algorithm first determines if 2 locators along the X-Z datum plane and 1 locator along the Y-Z datum plane can be placed. If 2 locators cannot be placed against the X-Z datum plane, the algorithm searches for positions of 2 locators against the Y-Z datum plane and 1 locator against the X-Z datum plane.

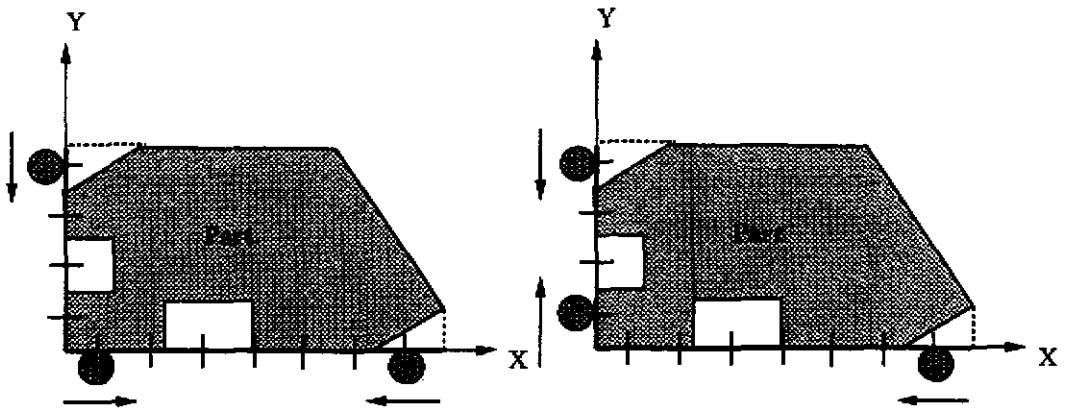


Figure 5-18: Part locating with locators

In any case, the algorithm generates a candidate locating plan starting with the most widely spread locators in order to achieve the better accuracy [Saku90].

5.9.3. Determining the Locator Height

At a candidate location, a locator's geometry should have a contact with the reference surface. The algorithm first identifies the minimum height of a locator to have a contact with the part. Figure 5-19 shows the minimum locator heights at various candidate locator positions along a reference surface. The minimum locator heights is 0.6" at positions a and b, and 2.6" at positions c and d. At the rest of the positions, the minimum locator height is zero.

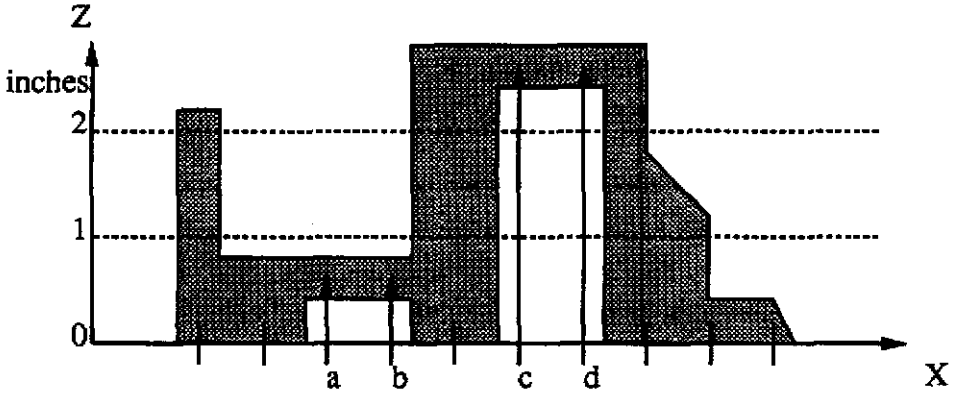


Figure 5-19: Determination of the minimum locator height

If the locator data base does not have a locator with the height equal to or taller than the minimum height, the candidate locating plan becomes invalid. If there exist multiple locator types taller than the specified height, a locator with the shortest height is selected. In our fixture planning, locators are not used to resist cutting forces but only used for locating purpose. When there exist various locator types in the data base, slender locators are preferred in order to avoid interference with clamps or cutter paths.

Figure 5-20 shows the actual locators selected at various candidate locator positions shown in 5-20 when locators are either 1 or 2 inches tall. At positions c and d, locators cannot be placed because the minimum height (2.6") is larger than the tallest locators (2"). At the rest of positions, 1 inch tall locators are selected.

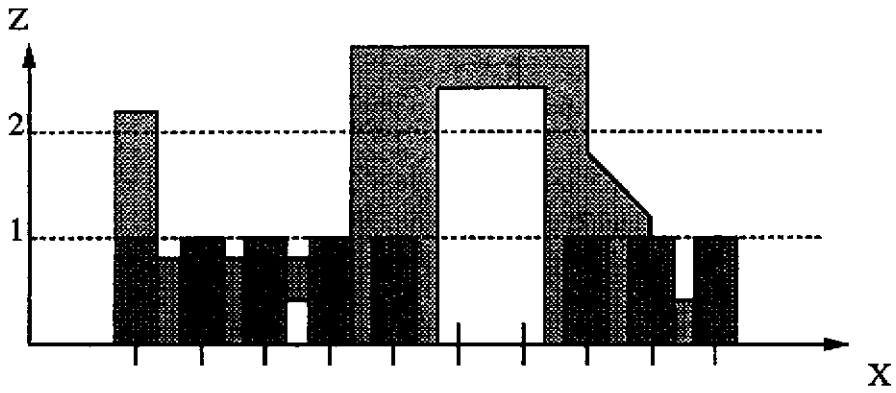


Figure 5-20: Selection of the locator at each position

5.9.4. Checking Interference against Clamps

At each candidate locator position, the geometry of a selected locator is first constructed in the local coordinate and is then transformed into the part coordinate by proper translation and orientation. Interference between a clamp and a locator can be quickly checked in 2D because their geometry can be projected as two rectangles on the base (see Figure 5-21). When a locator interferes with a clamp in 2D, the locator may not interfere with the clamp in space when it is placed under the clamp. Then, the interference checking algorithm can be applied between the clamp and the locator in 3D. If the locator interferes with any clamps, the candidate locating plan becomes invalid.

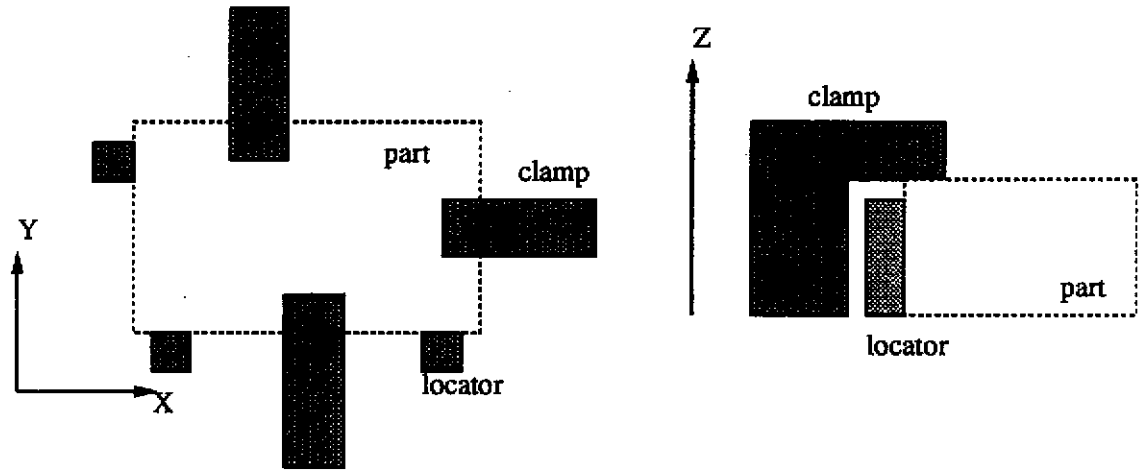


Figure 5-21: Interference checking between a clamp and a locator

5.9.5. Checking Interference against Cutter Paths

If the locator interferes with any cutter path, the candidate locating plan becomes invalid. A locator needs to be some distance away from the swept volumes of cutter paths in order to provide safety and allow some flexibility in fixture location and orientation during the actual assembly. The dimension of the locator geometry is enlarged to consider some clearance from the cutter paths. If the enlarged locator geometry interferes with any swept volume, the locator is either in interference with or too close to the cutter path.

Because the 3D interference checking algorithm is computationally expensive, it is used only when there is a possibility of interference. A comparison between the minimal and maximal x, y, and z coordinates of the locator and the swept volume can quickly detect the possibility of interference.

When a horizontal plate or an angle plate is used to orient the part, the interference checking between the geometry of a locator and a swept volume can be done in 2D because the swept volume is oriented parallel to the base plate (see Figure 5-21). The number of iterations required to detect interference between a locator and a swept volume is reduced from 36 (6 faces on a locator and 6 faces on a swept volume) to 1.

When a sine table is used to orient the part relative to the machine bed, 2D interference checking is not possible. For each set of faces of the clamp and the swept volume, the minimal and maximal x, y, and z coordinates are compared to detect the possibility of interference before using the 3D interference checking algorithm.

5.9.6. Remarks

Because the part is held by clamps, it is possible to pull out locators, if necessary after the part is located and clamped.

If a locating plan is not found due to interference with the cutter paths, the position of the locators can be determined by the same procedure without considering the cutter paths. If a locator in the locating plan interferes with the cutter paths, it needs to be pulled out after the part is located and clamped. However, since the contact between the part and the locator may have some friction induced due to clamping force during assembly, it may not be easy to pull locators out.

When locating a part cannot be completed with locators according to the 3-2-1 rule, a touch probe is used to complete locating, while the part is partially located by 2 locators placed against a side reference surface.

5.10. Rating Fixture Plans

Typically, the algorithm generates multiple fixture plans. Every fixture plan has the same number of clamps while the required clamping force and clamp location's are different from one plan to another.

Fixture plans in which the part is supported by a base plate and supports may exist for the same set up. Since fixture plans without supports are usually favored, all plans with supports are rated inferior to a fixture plan without supports.

A fixture plan with a smaller clamping force is favored because a part deflection problem due to clamping force is reduced, and the necessary clamping force gives a larger safety margin over the maximum clamping force. The algorithm orders fixture plans according to the magnitude of the clamping force required for each clamp. The less the clamping force, the higher the fixture plan is rated. If fixture plans both with and without supports exist, they are rated independently.

5.11. Remarks

5.11.1. Human Interface

Since the algorithm does not check part deflection, a human expert is required to detect any part deflection due to either clamping force or cutting force. Most part deflection due to cutting force cannot be prevented at all regardless of fixture plans. These types of part deflection can be detected by a human expert before generating any fixture plans. Thus, part deflection in a fixture plan is typically caused by clamping force when a clamp cannot be supported directly underneath.

When there exist fixture plans with or without supports, a human expert will prefer fixture plans with a base plate unless they violate any fixture constraints.

A human expert should carefully view the simulated part/fixture assembly of a fixture plan. When the part needs to be raised from a base plate, the algorithm tentatively places a support beneath each clamp, if the part geometry permits. For example, if a fixture plan is generated with two clamps, the part cannot only be supported stably with supports since at least 3 point contacts on a bottom reference surface are required in order to support and locate the part (see Figure 5-22). A human expert can determine the location of extra supports considering part geometry. Proper placement of supports may prevent part deflection.

If the part geometry does not permit the placement of clamps underneath a clamp or supports cannot support the part stably, a human expert may add extra supports or use a subplate instead considering the part's stability and/or part deflection due to clamping and/or cutting force. The height of the subplate should be the same as that of supports, and the overall size of a subplate should be determined so as not to interfere with clamps or locators.

If fixture plans highly rated by the algorithm have no problem of part deflection, the human expert can

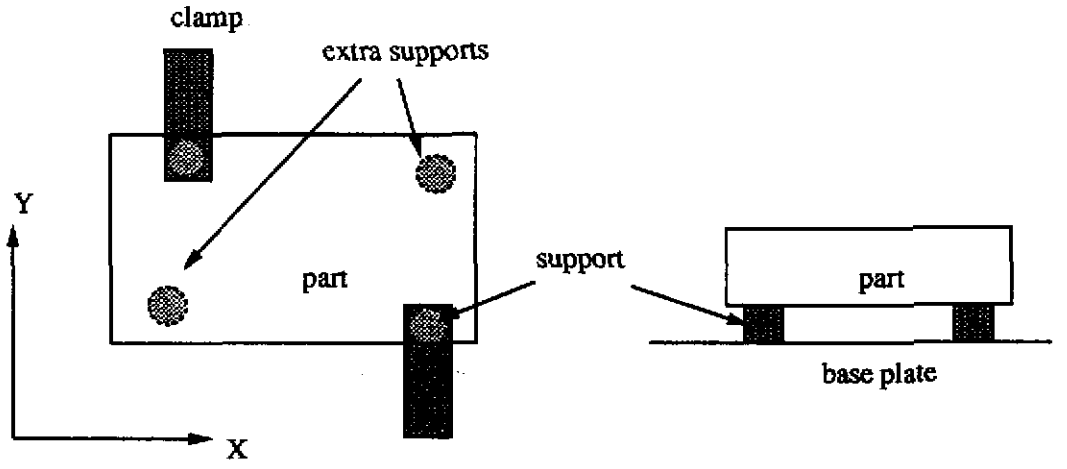


Figure 5-22: Placing extra supports in a fixture plan

quickly select the most favorable fixture plan as long as the plan also satisfies other constraints. However, if unacceptable part deflection exists in highly rated fixture plans, it could take time for a human expert to select a favorable fixture plan. Selecting a good fixture plan takes time because the human expert must carefully check any part deflection in fixture plans and determine a proper supporting method in order to prevent part deflection. When a human expert detects severe part deflection due to clamping force in every candidate fixture plan, the use of more clamps might avoid part deflection in some setups since the magnitude of required clamping force at a clamp is reduced. However, we do not consider this case in our system because the reduction of the magnitude of the cutting force is an inexpensive alternative.

Part deflection due to a cutting or clamping force may be automatically checked with a scheme based on heuristics with the the finite element method (FEM). Because FEM is computationally expensive, a fast scheme with appropriate simplification needs to be developed. Sakurai suggested applying FEM in 2D using a large mesh size to speed up the analysis for measuring part deflection [Sakurai 90]. Part deflection due to cutting force can be checked before generating any fixture plans by assuming that the part's resting reference surface is glued to the base plate. If the cutting force is directed toward the base plate and well supported, there is no possibility of part deflection due to the cutting force. The possibility of part deflection due to the clamping force needs to be checked only when the clamp location is poorly supported or clamping force's direction passes through the concavity of the part. Once a candidate fixture plan is generated, part deflection can be checked with every clamp at its locations against critical cutter paths whose force is directed toward the part's thin area.

5.11.2. Clamp Assembly

Although the algorithm determines clamp locations before the supports and locators' locations, supports and locators should be placed on the base plate before any clamps during fixture assembly.

Each clamp in a fixture plan is oriented perpendicular to the edge of a clampable part face at the clamp location. Depending on the limitation of T-slots or pin holes of the base plate and the clamp type, it may

not be possible to install a clamp at the specified location and orientation. Because the algorithm determines the location of the clamp with some clearance from the part and cutter paths, the clamp can be installed at a different location and/or orientation from the specified orientation and location.

Chapter 6
Fixture planning with a Vise

6.1. Introduction

In this chapter, we describe an algorithm to automatically generate fixture plans with a vise. A vise consists of a fixed jaw and a movable jaw. In order to accurately locate the part, the fixed jaw should contact a reference side of the part and the movable jaw should contact a surface parallel to the reference surface, face to face with the fixed jaw. For a complete fixture plan with a vise, the location of each jaw, the clamping force and the height of parallel bars should be determined.

Section 2 describes the algorithm developed to search and generate fixture plans with a vise. Section 3 through 10 discusses reasoning and tools used in various steps within the algorithm. Section 11 concludes this chapter with remarks.

6.2. Overview of the Algorithm

The algorithm assumes that the part's reference surfaces are only on the datum reference planes of the part coordinate. Thus, a fixed jaw should contact the part's reference side on either the X-Z datum plane or the Y-Z datum plane of the part coordinate. A movable jaw should contact the part's surface parallel to the reference side that the fixed jaw contacts. Parallel bars or a base plate should have contact with the part's bottom reference surface for accurate locating.

As discussed in Chapter 4, a jaw is modeled as a rectangular block, and its origin is at the center of the bottom face. A fixture plan with a vise specifies the location of a fixed jaw, a movable jaw, the clamping force, and the parallel bars' height and locations. The locations of vise jaws and parallel bars are given in the part coordinate. The figure of Figure 6-1 shows how a jaw is described in the local coordinate. The second figure shows its origin's location in the part coordinate when the fixed jaw is placed against the part's side reference surface on X-Z datum plane.

Because the part's reference side is parallel to the X-Z (or Y-Z) datum plane of the part coordinate, y (or x) coordinate is the same on the surface. The y coordinates of both jaw locations can be easily determined by jaw width and the y coordinates of contact surface between the jaw and the part. However, determining the x and z coordinates of the jaw location requires complex geometric reasoning in consideration of part geometry and cutter paths. Because we are only concerned with determining two coordinates (x and z), a

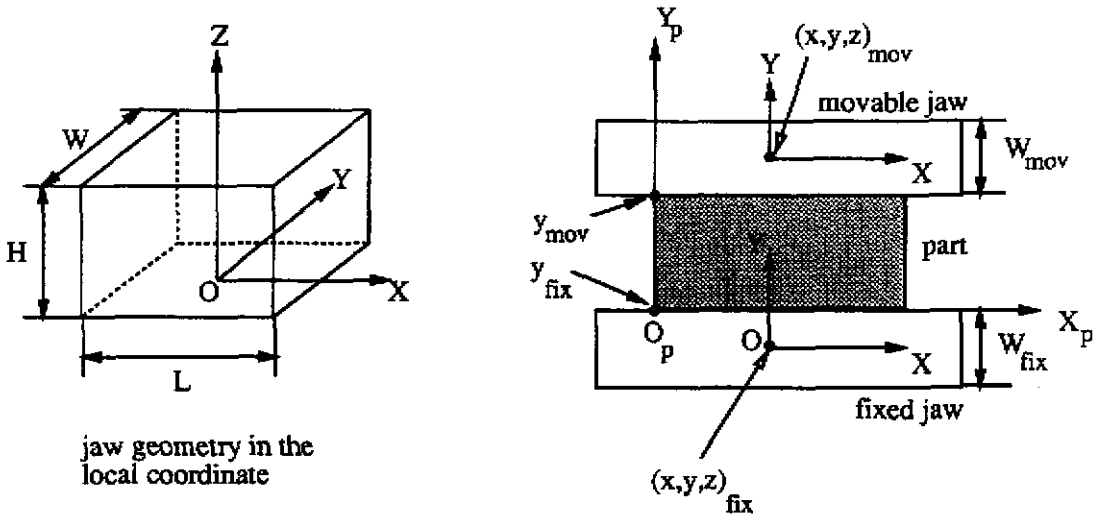


Figure 6-1: Coordinates of jaw locations in the part coordinate

2D method is developed for the simpler geometric reasoning. The method maps 3D geometric information from the cutter paths and part geometry onto a plane parallel to both part surfaces for the jaw placement and performs geometric reasoning on the plane to determine the jaw location.

A contact plane is a plane that contains part surface(s) for either a fixed or a movable jaw to contact. The contact plane is always parallel to either the X-Z datum plane or the Y-Z datum plane of the part coordinate and is also perpendicular to the base plate. Because a fixed jaw should contact a part's reference side, there exists a single contact plane against either X-Z or Y-Z datum plane of the part coordinate. For the contact plane of the fixed jaw, there may exist more than one contact plane for a movable jaw. Figure 6-2 shows a part geometry in which there exist multiple contact planes for the location of a fixed jaw and a movable jaw. For brevity, the figure shows a top view of a prismatic part. Each contact plane becomes a line parallel to either the X or Y axis of the part coordinate.

In order to prevent any part rotation during clamping after the part is located, a vise should have a common area between the contact areas when the part is clamped by the vise. In each contact plane, the algorithm first identifies the maximal contact area for each jaw and then identifies the common area as an intersection when the two maximal contact areas are overlapped on a plane parallel to both contact areas.

The part geometry and swept volumes of cutter paths are mapped onto the contact plane as bounding rectangles parallel to the base plate. The algorithm identifies every collision-free contact area for the jaw placements on the common area while avoiding obstacles. On each collision-free area, the location of jaws in the part coordinate is determined so that the jaw can have the maximum contact area with the common area. The dimension of parallel bars is easily determined in consideration of the jaw location relative to the part. The actual contact area between the jaw and the part is identified, and the clamping force is estimated with the simplified force model with 3 pont contacts on the contact area.

When multiple fixture plans are generated, a plan with a smaller clamping force has less chance of part

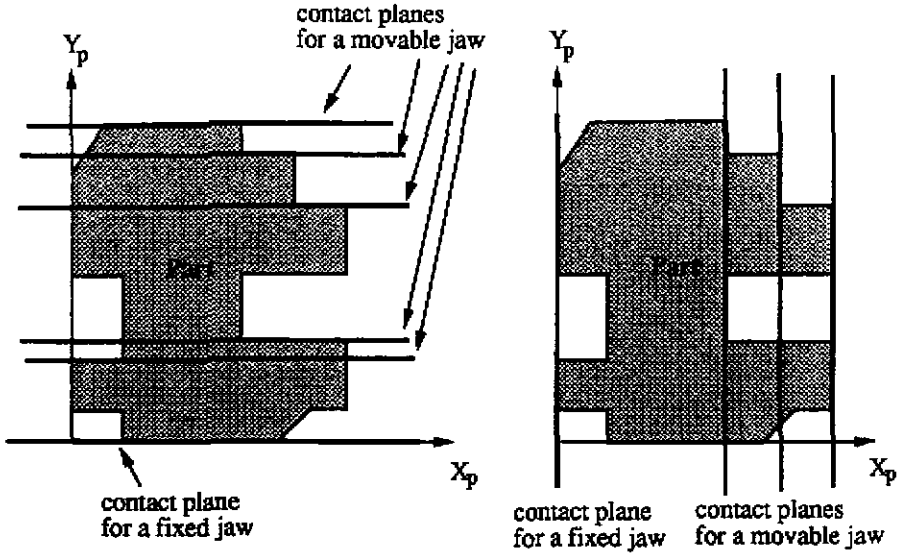


Figure 6-2: Contact planes for vise jaws

deflection and gives a larger safety margin from the maximal clamping force of a jaw. The algorithm orders each plan by the magnitude of clamping force so that a tool designer can inspect starting from the plan with the least clamping force. Every plan generated by the algorithm satisfies geometric, kinematic, and force constraints in fixturing. Thus, a human expert needs to check any part deflection due to clamping/cutting force and select the most favorable fixture plan.

Figure 6-3 shows an algorithm for the generation of a fixture plan with a vise. Details of geometric reasonings and analysis in various steps in the algorithm will be described in the following sections. As we mentioned earlier, there are two side reference surfaces on the part with which a fixed jaw can have contact. The same algorithm is applicable to either case regardless of which reference surface a fixed jaw is placed against.

Here, we only describe the geometric reasoning when a fixed jaw is placed against the part's reference surface on the X-Z datum plane. Every coordinate in geometric reasoning is expressed in the part coordinate. When a fixed jaw is placed against the part's reference surface on the Y-Z datum plane, the geometric reasoning to identify contact areas and determine the jaw location in the part coordinate is the same except that x coordinates should be replaced by y coordinates in the reasoning.

6.3. Selection of a Vise Type

If there are multiple vise types in the modular fixturing system, the algorithm selects a vise type with the least clamping force first since its assembly can often be done faster and easier than the other vise types. When no valid fixture plans are generated with the selected vise type, the algorithm selects another vise type and retries until at least a valid fixture plan is generated.

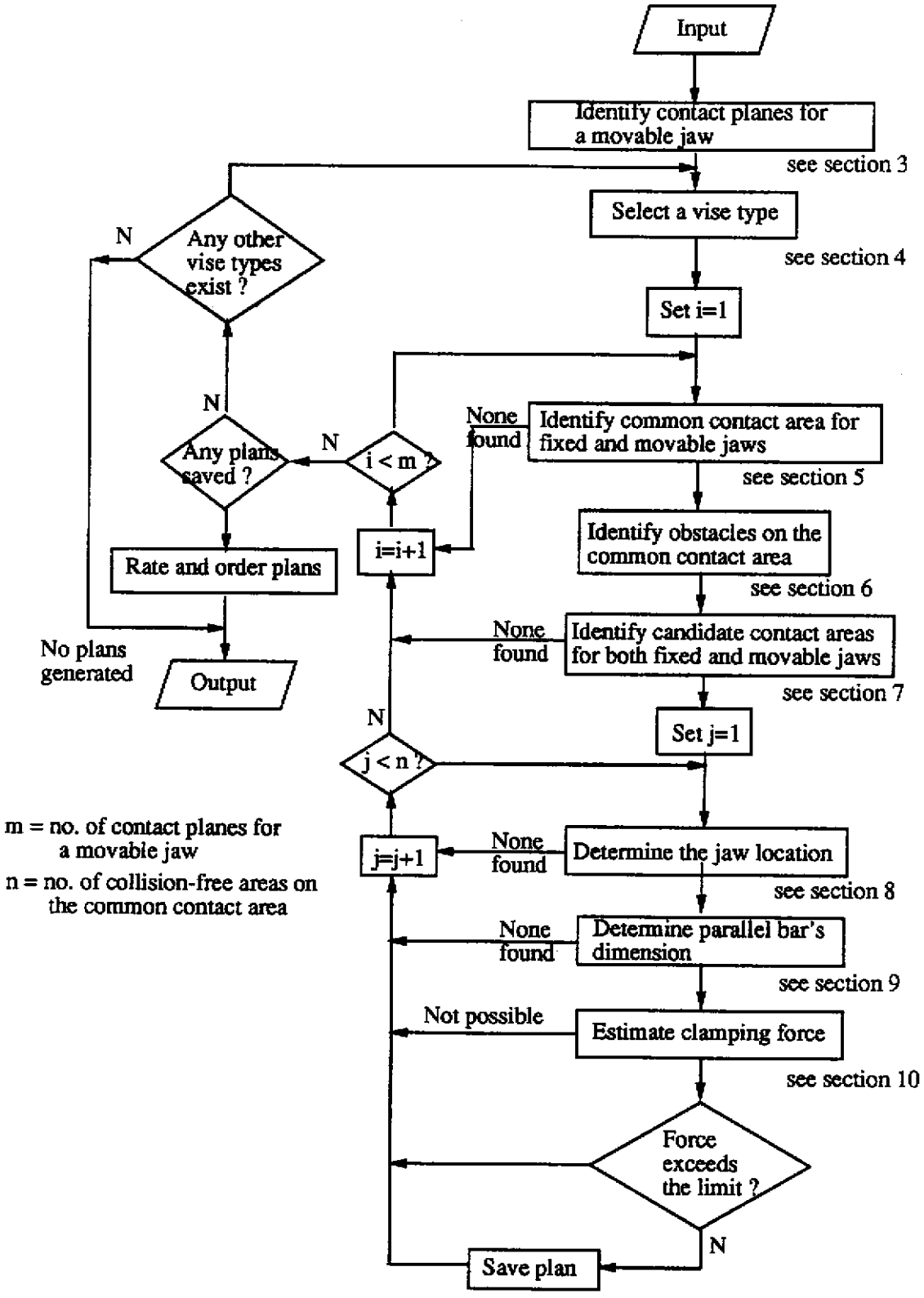
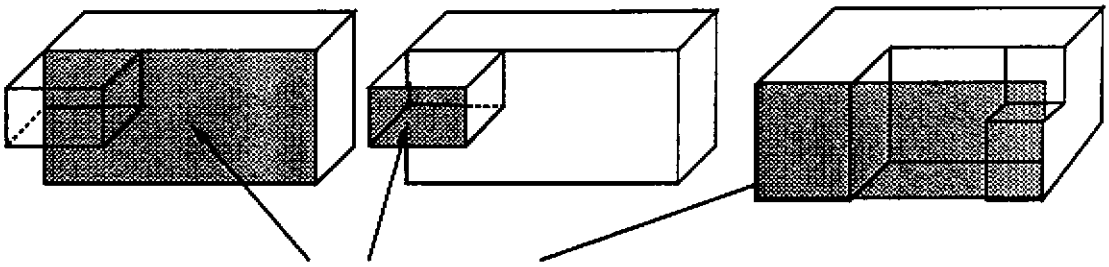


Figure 6-3: An algorithm for a fixture plan with a vise

6.4. Identification of the Common Contact Area

A contact area is defined as a rectangle that bounds every part face on the contact plane (see figure 6-4). The rectangle lies within the contact plane and is oriented parallel to the X-Y datum plane.



Examples of bounding contact areas on particular contact planes

Figure 6-4: Maximal contact areas on contact planes on given different examples of parts

A contact area may be composed of multiple faces and/or concave faces. The coordinates of the contact area can be found by taking the minimal and maximal x and z coordinates among every part face on the contact plane. Let x_{min}^{fix}, x_{max}^{fix}, z_{min}^{fix}, and z_{max}^{fix} be the minimal and maximal x and z coordinates of the vertices of the contact area for a fixed jaw. Also, let x_{min}^{mov}, x_{max}^{mov}, z_{min}^{mov}, and z_{max}^{mov} be the minimal and maximal x and z coordinates of the vertices of the contact area for a movable jaw.

Both a fixed and movable jaw's bottom surface should have contact with the base plate. Let y_{pl} be the y coordinate of the contact plane for the movable jaw and y_{max} the maximal y coordinate of the part in the part coordinate. If $y_{pl} < y_{max}$ and $z_{min}^{mov} > 0$, a movable jaw cannot have contact with the contact area due to physical limitations (see Figure 6-5).

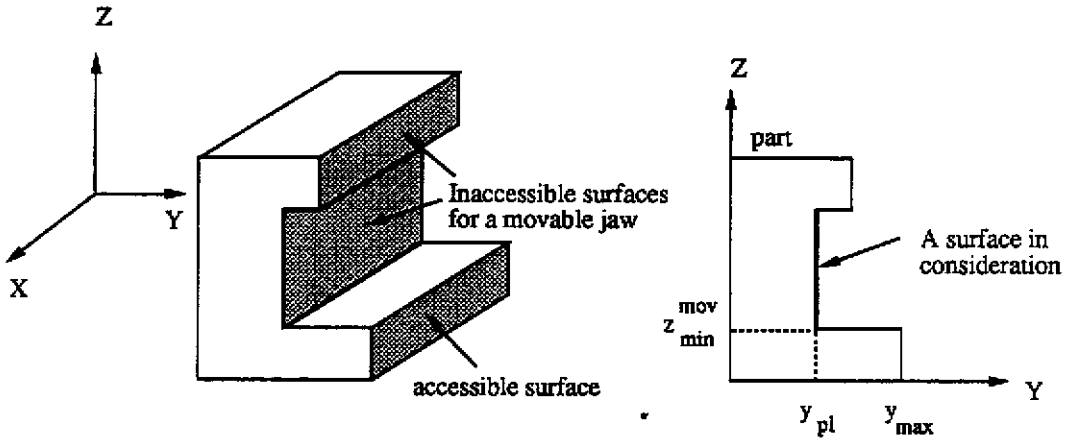


Figure 6-5: Accessible and inaccessible part surfaces for a movable jaw

When vise jaws are placed against the part, a movable jaw should not cause the part to rotate during clamping. In Chapter 3, we have shown that the contact area between a fixed jaw and the part and the contact area between a movable jaw and the part should have a common area when both contact areas are overlapped onto each other in order to avoid any part rotation during clamping.

The following reasoning is used to identify dimensions of the common area (cm) between two contact areas for fixed and movable jaws (see Figure 6-6). Let x^{cm}_{min}, x^{cm}_{max}, z^{cm}_{min}, and z^{cm}_{max} be the minimal and maximal x and z coordinates of the vertices of the bounding rectangle for the common contact area.

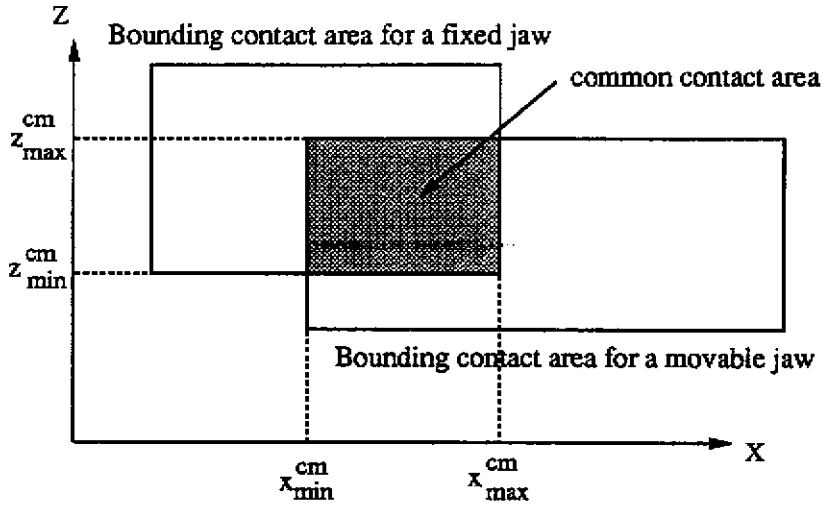


Figure 6-6: Identifying the common contact area when both bounding contact areas are projected onto a plane parallel to the X-Z datum plane

Then, the dimension of the common contact area can be determined as follows.

- If $x^{mov}_{min} \le x^{fix}_{min}$, $x^{cm}_{min} = x^{fix}_{min}$. Otherwise $x^{cm}_{min} = x^{mov}_{min}$.
- If $x^{mov}_{max} \ge x^{fix}_{max}$, $x^{cm}_{max} = x^{fix}_{max}$. Otherwise $x^{cm}_{max} = x^{mov}_{max}$.
- If $z^{mov}_{min} \le z^{fix}_{min}$, $z^{cm}_{min} = z^{fix}_{min}$. Otherwise $z^{cm}_{min} = z^{mov}_{min}$.
- If $z^{mov}_{max} \ge z^{fix}_{max}$, $z^{cm}_{max} = z^{fix}_{max}$. Otherwise $z^{cm}_{max} = z^{mov}_{max}$.

If $x^{fix}_{min} \ge x^{mov}_{max}$ or $x^{fix}_{max} \le x^{mov}_{min}$ or $z^{fix}_{min} \ge z^{mov}_{max}$ or $z^{fix}_{max} \le z^{mov}_{min}$, there is no common contact area. Because the part will rotate when clamped by a movable jaw, the current set of contact planes cannot generate any valid fixture plan.

Let L_{jaw} and H_{jaw} be the horizontal length and the vertical length of the jaw, respectively. If $z^{cm}_{min} \ge H_{jaw}$, a jaw cannot touch the common contact area at all (see figure 6-7).

6.5. Identification of Obstacles

So far, the common contact area for both jaws have been identified without considering interference with cutter paths and part geometry. Cutter paths and any part geometry that prevents jaw placement against the part are considered as obstacles.

The simple geometric reasoning to identify inaccessible areas on the common contact area has been developed in plane rather than in space. An obstacle due to either cutter paths or part geometry is represented as a bounding rectangle within the common contact area. Thus, the key idea is to determine jaw location while avoiding any obstacles on the common contact area.

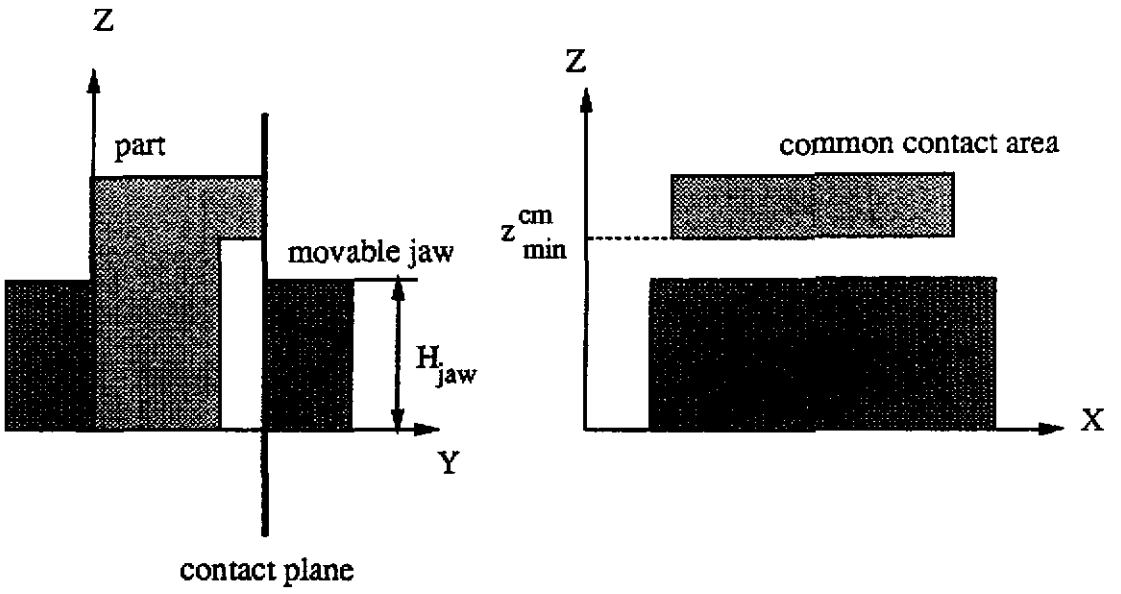


Figure 6-7: A case when a jaw cannot touch a common contact area

Let x^{obs}_{min}, x^{obs}_{max}, z^{obs}_{min}, and z^{obs}_{max} be the minimal and maximal x and z coordinates of an obstacle on the common contact area. Note that $z^{obs}_{max} = z^{cm}_{max}$ for every obstacle because the jaw does not have an access above z^{obs}_{min}. Since vise jaws are placed face to face, an obstacle that limits the location of a jaw will also limit the location of the other jaw simultaneously.

6.5.1. Obstacles from Cutter Paths

As discussed in Chapter 4, a swept volume of a cutter path is represented in space as a rectangular block constructed with the cutter diameter and starting and ending coordinates of the path.

When a cutter path interferes with the common contact area.

The intersection checking routine in the NOODLES library [Gursoz 91] can be used to detect interference (int) between the swept volume and the common contact area. Let x^{int}_{min}, x^{int}_{max}, and z^{int}_{min} be the minimal and maximal x and z coordinates of the intersected area between the swept volume and the rectangle.

Let y_{fix} and y_{mov} be the y coordinates of the contact planes for a fixed jaw and a movable jaw, respectively. y_{fix} is always zero because a fixed jaw is placed against the part's side reference surface on the X-Z datum plane of the part coordinate. If a swept volume (sv) interferes with the common contact area on the contact plane for either a fixed jaw or a movable jaw, let x^{sv}_{min}, x^{sv}_{max}, and z^{sv}_{min} be the minimal and maximal x and z coordinates of the vertices on the swept volume whose y coordinates < y_{fix} for the fixed jaw or y coordinates > y_{mov} for the movable jaw. The coordinates of the obstacle due to the swept volumes of cutter paths can be determined by the following reasoning:

- If $x^{sv}_{min} < x^{int}_{min}$, then $x^{obs}_{min} = x^{sv}_{min}$. Otherwise, $x^{obs}_{min} = x^{int}_{min}$.

- If $x^{sv}_{max} > x^{int}_{max}$, then $x^{obs}_{max} = x^{sv}_{max}$. Otherwise, $x^{obs}_{max} = x^{int}_{max}$.
- If $z^{sv}_{min} < z^{int}_{min}$, then $z^{obs}_{min} = z^{sv}_{min}$. Otherwise, $z^{obs}_{min} = z^{int}_{min}$.

Figure 6-8 shows obstacles mapped on the common contact area within a contact plane for a fixed jaw and a movable jaw according to the above reasoning when a cutter path interferes with both contact planes.

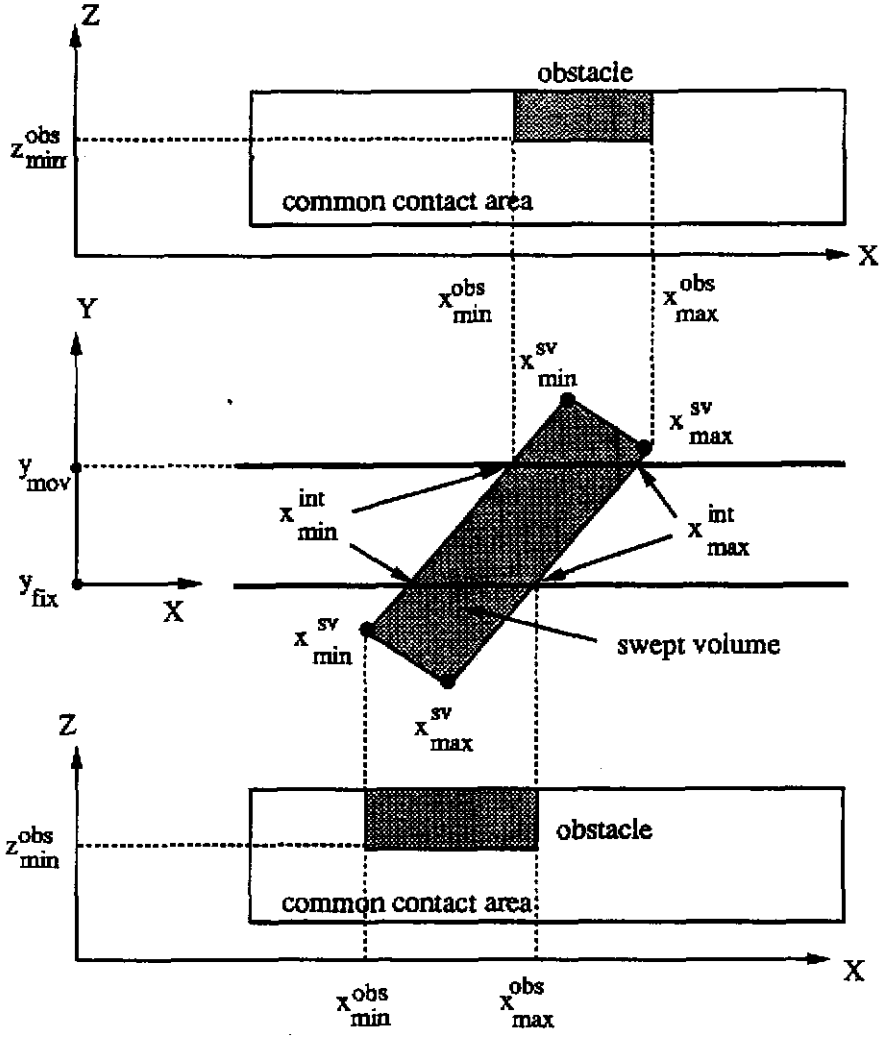


Figure 6-8: 2D obstacle mapping: cutter paths interfere with the common contact area

When a cutter path does not interfere with the common contact area

Although a cutter path does not interfere with the common contact area, it may limit the placement of a jaw depending on its location. Let x^{sv}_{min}, x^{sv}_{max}, y^{sv}_{min}, y^{sv}_{max}, and z^{sv}_{min} be the minimal and maximal x, y, and z coordinates of the swept volume.

When $z^{sv}_{min} < z^{cm}_{max}$ and when either $y^{sv}_{min} < y_{fix}$ or $y^{sv}_{min} > y_{mov}$, if the following conditions are met, a cutter path will limit the jaw location and the dimension of the obstacle can be determined as follows:

- If $x^{sv}_{min} < x^{cm}_{max}$ and $x^{sv}_{min} > x^{cm}_{min}$, then $x^{obs}_{min} = x^{sv}_{min}$ and $x^{obs}_{max} = x^{cm}_{max}$.
- If $x^{sv}_{max} < x^{cm}_{max}$ and $x^{sv}_{max} > x^{cm}_{min}$, then $x^{obs}_{min} = x^{cm}_{min}$ and $x^{obs}_{max} = x^{sv}_{max}$.
- If $x^{sv}_{max} < x^{cm}_{max}$ and $x^{sv}_{min} > x^{cm}_{min}$, then $x^{obs}_{min} = x^{sv}_{min}$ and $x^{obs}_{max} = x^{sv}_{max}$.

For each obstacle, $z^{obs}_{min} = z^{sv}_{min}$. Figure 6-9 shows obstacles mapped onto the common contact area within a contact plane for a fixed jaw and a movable jaw according to the above reasoning when a cutter path does not interfere with either contact plane.

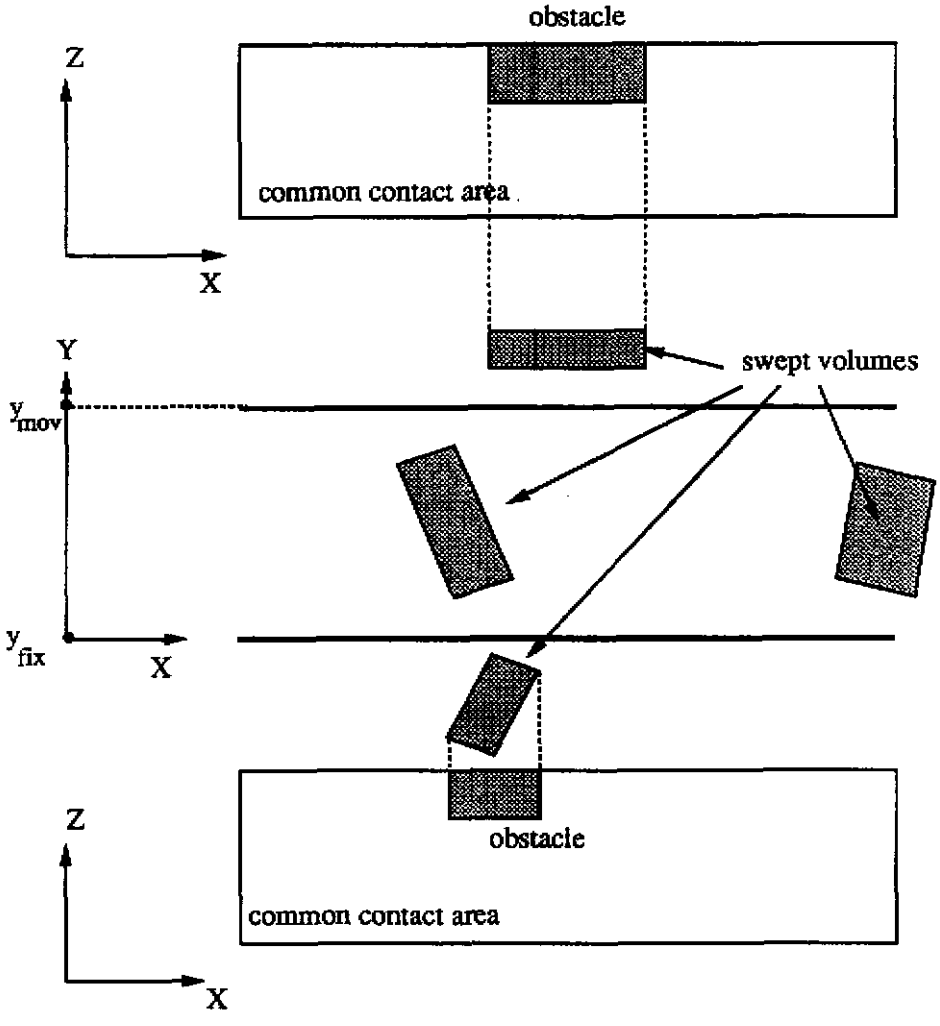


Figure 6-9: 2D obstacle mapping: cutter paths do not interfere with the common contact area

6.5.2. Obstacles from Part Geometry

Because a fixed jaw is placed against a reference side on the datum plane of the part coordinate, the jaw is always in contact with the bounding block of a part. Thus, there is no interference between the part and the jaw. Also, if a movable jaw is placed against the bounding block of the part, there is no interference between the part and the jaw. However, a movable jaw may be placed within the part concavity and there is a danger of interference between the jaw and the part.

In our reasoning, each part face whose minimal y coordinate $\geq y_{mov}$ limits the placement of the movable jaw. Each face is bounded by a convex rectangle and mapped onto the common contact area as an obstacle. Figure 6-10 shows how part faces can be represented as obstacles on the common contact area when a movable jaw is placed within the part concavity. If the part face is perpendicular to the contact plane, it can be ignored because it becomes a line on the common contact area and is redundant in the reasoning (the line also belongs to other obstacles.).

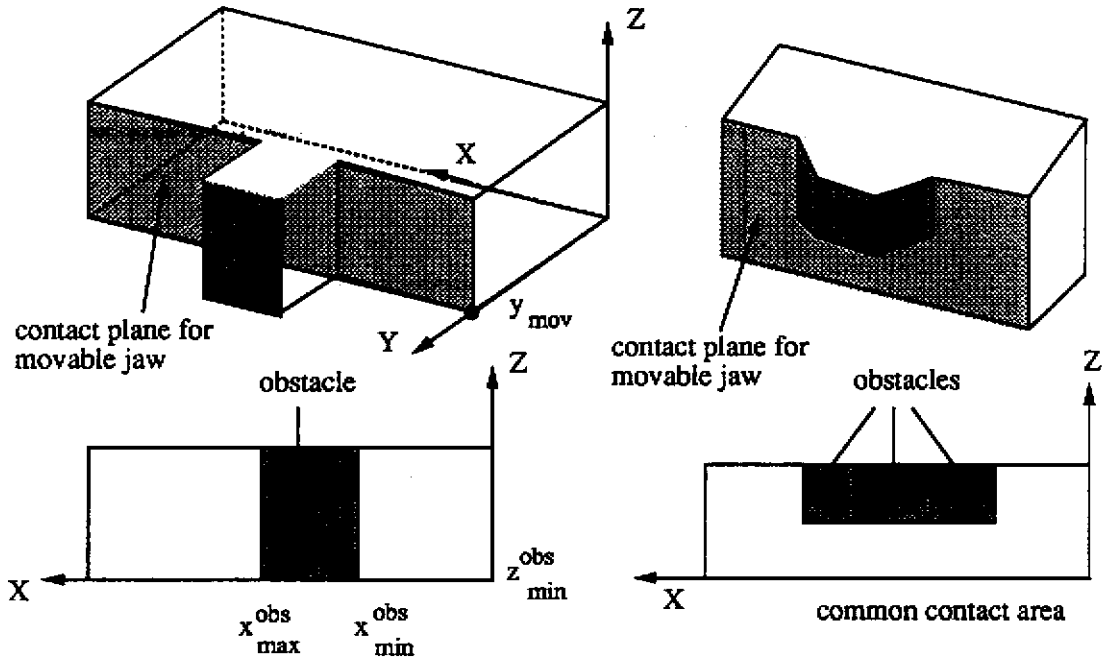


Figure 6-10: Obstacles due to part geometry on the common contact area

Let x_{min}^{face}, x_{max}^{face}, and z_{min}^{face} be the minimal and maximal x and z coordinate of a part face. Then each part face can be represented as a rectangular obstacle. The coordinates of the obstacle is found by the following relationships.

$$x_{min}^{obs} = x_{min}^{face}, x_{max}^{obs} = x_{max}^{face}, \text{ and } z_{min}^{obs} = x_{min}^{face}.$$

6.6. Identifying Collision-free Contact Areas for Jaw Placement

Once obstacles are identified on the common contact area, our goal is to identify collision-free areas for jaw placement. We have developed geometric reasoning to identify every possible collision-free area on the common contact area without redundancy (by redundancy, we mean that a collision-free area is not completely enclosed by another collision-free area.)

On the contact plane, a jaw can be represented as a rectangle parallel to the X-Y datum plane. The contact area between the jaw and the common contact area can also be represented as a rectangle. Since obstacles are represented in 2D and a jaw can be represented as a rectangle, finding a collision-free (cf) area for jaw placement becomes a 2D problem.

Let x^{cf}_{min}, x^{cf}_{max}, z^{cf}_{min}, and z^{cf}_{max} be the minimal and maximal x and z coordinates of a collision-free area on the common contact area. Due to the physical limitations of the vise, the collision-free area should be accessible from the base plate, always $z^{cf}_{min} = z^{cm}_{min}$.

When there are no obstacles on the common contact area, the entire common contact area is accessible for jaw placement. This happens when every swept volume of cutter paths lies between contact planes. For example, drilling a hole or making a slot on the part may not limit the jaw placement on the common area at all. The dimension of the collision-free area is the same as that of the common contact area. Thus, $x^{cf}_{min} = x^{cm}_{min}$, $x^{cf}_{max} = x^{cm}_{max}$, and $z^{cf}_{max} = z^{cm}_{max}$. Because any other candidate areas would be completely enclosed by the current area, the number of collision-free areas becomes one.

However, one or more obstacles typically exist on the common contact area and there exists more than one collision-free area. The algorithm first identifies the collision-free area outside of the bounding rectangle of obstacles. Then, the algorithm exhaustively searches every possible collision-free area without redundancy.

6.6.1. Global Identification of Collision-free Areas

Let x^{g}_{min}, x^{g}_{max}, and z^{g}_{min} be the minimal and maximal x and z coordinates among obstacles. The following geometric reasoning is used to identify every possible collision-free area outside of the bounding rectangle of obstacles:

- If $x^{g}_{min} > x^{cm}_{min}$, then $x^{cf}_{min} = x^{cm}_{min}$, $x^{cf}_{max} = x^{g}_{min}$, and $z^{cf}_{max} = z^{cm}_{max}$
- If $x^{g}_{max} < x^{cm}_{max}$, then $x^{cf}_{min} = x^{g}_{max}$, $x^{cf}_{max} = x^{cm}_{max}$, and $z^{cf}_{max} = z^{cm}_{max}$
- If $z^{g}_{min} > z^{cm}_{min}$, then $x^{cf}_{min} = x^{cm}_{min}$, $x^{cf}_{max} = x^{cm}_{max}$, and $z^{cf}_{max} = z^{g}_{min}$

Figure 6-11 shows collision-free areas on the common contact area when multiple obstacles exist. If a single obstacle exists on the common contact area, the reasoning is sufficient to find every possible collision-free area.

6.6.2. Local Identification of Collision-free Areas

When there is more than one obstacle, other collision-free areas exist that could not be identified by global searching. Often, numerous obstacles may exist on the common contact area, and it becomes difficult to identify every collision-free areas. Here, we present a systematic search method that can identify "unique" collision-free areas. This is done by considering two obstacles at a time. While collision-free areas are identified from every two obstacles, other obstacles are used to check the redundancy. If the collision-free area is found redundant, it is ignored.

Two obstacles may or may not be overlapped. For convenience, geometric reasoning is developed for each case. Let x^{a}_{min}, x^{a}_{max} z^{a}_{min}, x^{b}_{min}, x^{b}_{max}, and z^{b}_{min} be the minimal and maximal x and z coordinates of two obstacles where $x^{a}_{min} \leq x^{b}_{min}$.

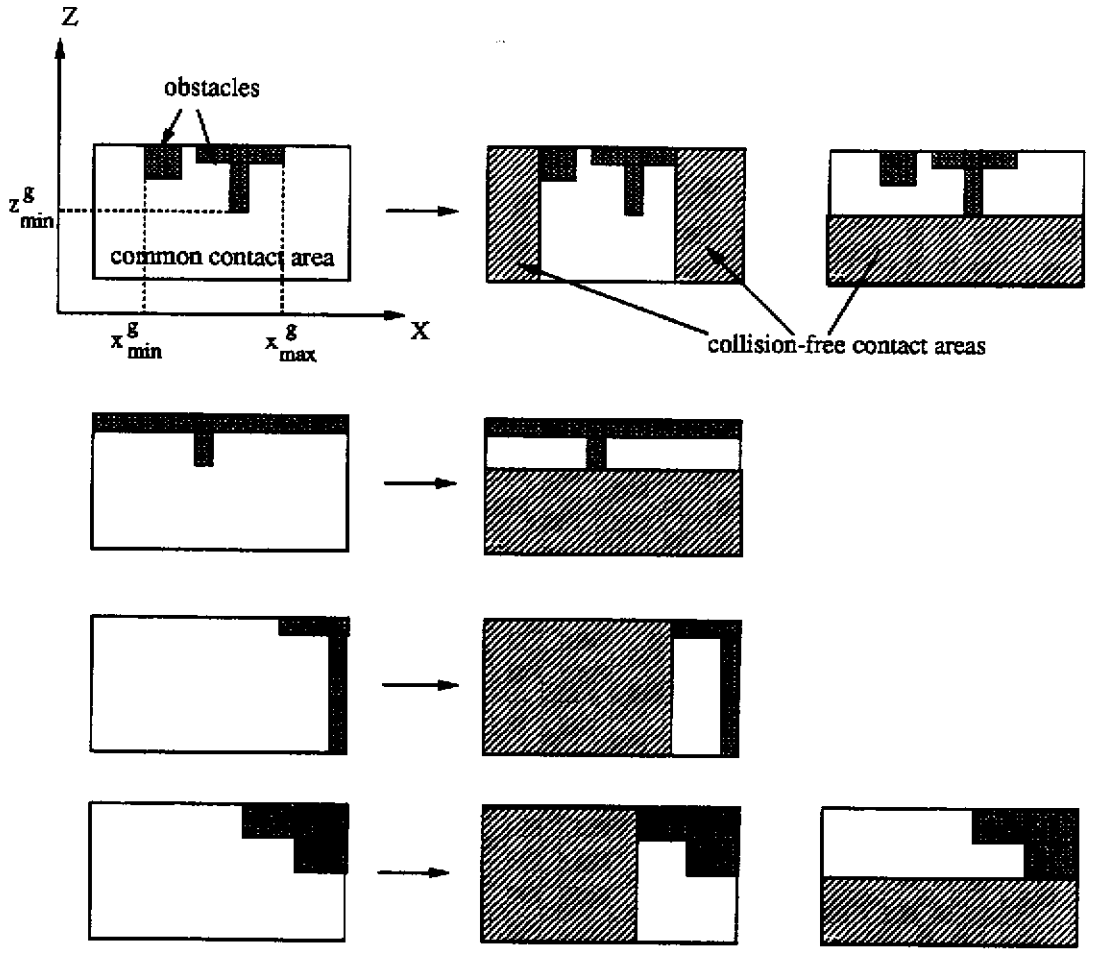


Figure 6-11: Globally found collision-free areas for the jaw placement

A. When obstacles are not overlapped (that is, when $x^a_{max} \leq x^b_{min}$) (see Figure 6-12)

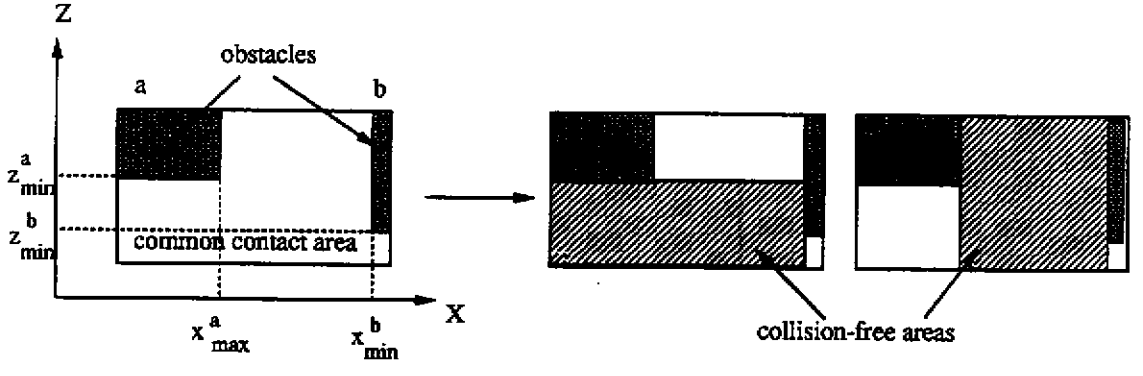


Figure 6-12: Identifying collision-free areas with non-overlapped obstacles

1. A collision-free area is found between two obstacles and its coordinate is found as follows.

$x^{cf}_{min} = x^a_{max}$, $x^{cf}_{max} = x^b_{min}$, and $z^{cf}_{max} = z^{cm}_{max}$.

If $x^b_{min} - x^a_{max} < L_{jaw}$, the area is not accessible to the jaw.

Because we have considered two obstacles at a time, other obstacles may limit the current collision-free area. Let z^{nobs}_{min} be the minimal z coordinate of obstacles that interfere with the collision-free area. If the current area interferes with the other obstacles, $z^{cf}_{max} = z^{nobs}_{min}$. If $z^{nobs}_{min} < z^a_{min}$ or $z^{nobs}_{min} < z^b_{min}$, the area is redundant.

2. If $z^a_{min} > z^b_{min}$, the coordinates of the collision-free area are found as follows:

$x^{cf}_{min} = x^{cm}_{min}$, $x^{cf}_{max} = x^b_{max}$, and $z^{cf}_{max} = z^a_{min}$. Otherwise, $x^{cf}_{min} = x^a_{max}$, $x^{cf}_{max} = x^{cm}_{max}$, and $z^{cf}_{max} = z^b_{min}$. If the area interferes with the other obstacles, the area becomes redundant.

B. When obstacles are overlapped (that is, when $x^b_{min} > x^a_{max}$) (see Figure 6-13)

Note that $x^a_{min} \leq x^b_{min}$. This can be divided into two cases - when $x^a_{min} = x^b_{min}$ or when $x^a_{min} < x^b_{min}$. In each case, the coordinates of the collision-free contact area are different depending on how two obstacles are overlapped. If the collision-free contact area interferes with the other obstacles, it is a redundant area.

<B.1 When $x^a_{min} = x^b_{min}$>

If $x^a_{max} > x^b_{max}$ and $z^a_{min} > z^b_{min}$, the coordinates of the collision-free area are found as follows.

$x^{cf}_{min} = x^b_{max}$, $x^{cf}_{max} = x^{cm}_{max}$, and $z^{cf}_{max} = z^a_{min}$.

If $x^a_{max} < x^b_{max}$ and $z^a_{min} < z^b_{min}$, the coordinates of the collision-free area are found as follows.

$x^{cf}_{min} = x^a_{max}$, $x^{cf}_{max} = x^{cm}_{max}$, and $z^{cf}_{max} = z^b_{min}$.

<B.2 When $x^a_{min} < x^b_{min}$>

Case 1: If $x^a_{max} > x^b_{max}$

If $z^b_{min} < z^a_{min}$, two collision-free areas exist. The coordinates of the first collision-free area are found as follows.

$x^{cf}_{min} = x^{cm}_{max}$, $x^{cf}_{max} = x^b_{max}$, and $z^{cf}_{max} = z^a_{min}$.

The coordinates of the second collision-free area are found as follows.

$x^{cf}_{min} = x^b_{max}$, $x^{cf}_{max} = x^{cm}_{max}$, and $z^{cf}_{max} = z^a_{min}$.

Case 2: If $x^{cf}_{max} = x^b_{max}$

If $z^b_{min} < z^a_{min}$, the coordinates of the first collision-free area is found as follows.

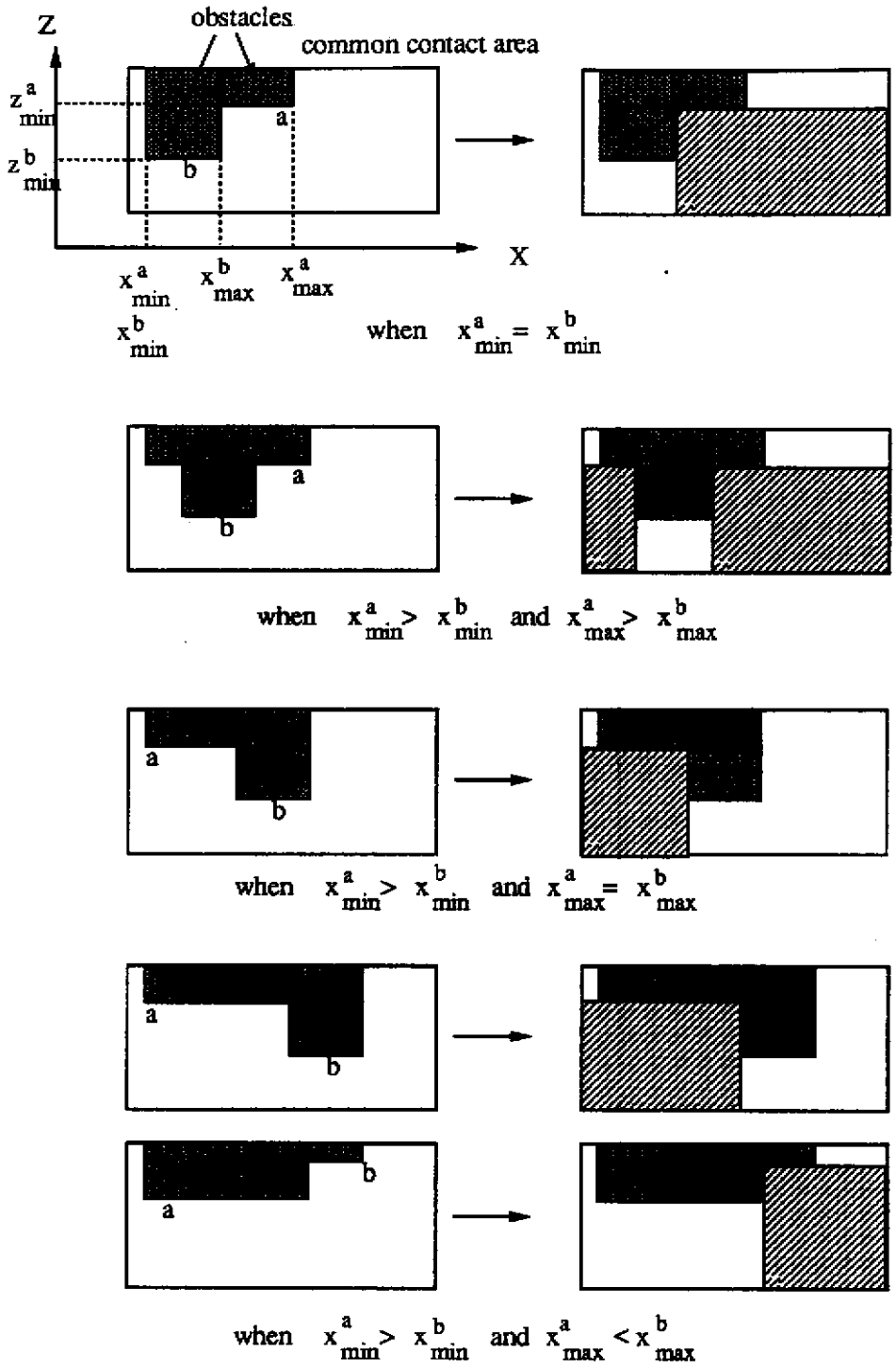


Figure 6-13: Identifying collision-free areas with overlapped obstacles

$x^{cf}_{min} = x^{cm}_{max}$, $x^{cf}_{max} = x^{b}_{max}$, and $z^{cf}_{max} = z^{a}_{min}$.

Case 3: If $x^a_{max} < x^b_{max}$

If $z^{b}_{min} < z^{a}_{min}$, the coordinates of the first collision-free area are found as follows.

$x^{cf}_{min} = x^{cm}_{max}$, $x^{cf}_{max} = x^{b}_{max}$, and $z^{cf}_{max} = z^{a}_{min}$. Otherwise, $x^{cf}_{min} = x^{a}_{max}$, $x^{cf}_{max} = x^{cm}_{max}$, and $z^{cf}_{max} = z^{b}_{min}$.

Figure 6-14 shows a few examples of collision-free contact areas globally and locally identified by the algorithm.

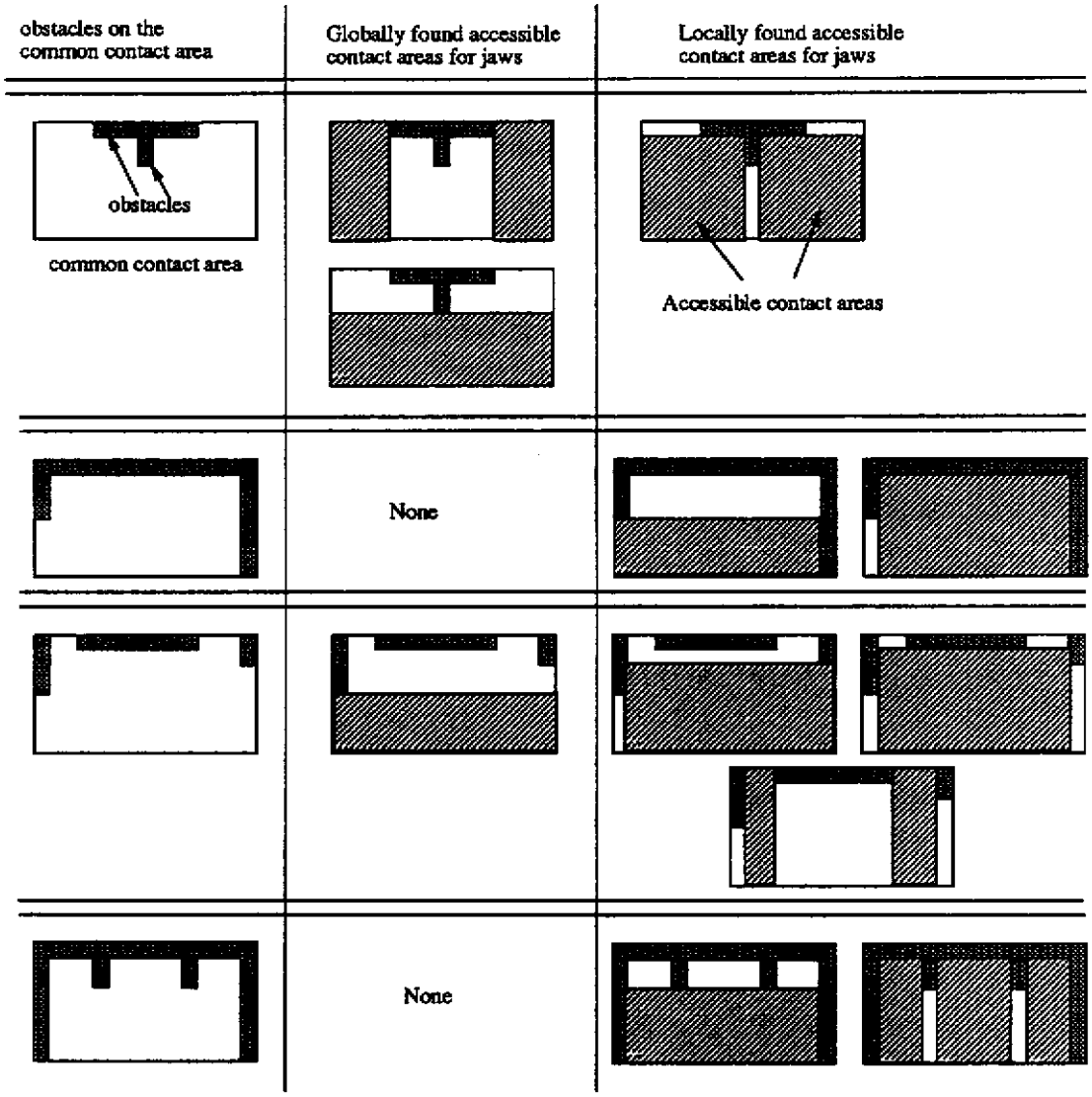


Figure 6-14: Collision-free contact areas on the common contact area

6.7. Determining the location of vise jaws

Each collision-free contact area is used to generate a candidate fixture plan. Numerous ways exist to place a jaw against the collision-free contact area. We have developed geometric reasoning to determine the jaw location in order to have maximal contact area between the jaw and the collision-free contact area. Once again, we only describe the geometric reasoning when the jaw is placed against the collision-free contact area parallel to the X-Z datum plane of the part coordinate.

Let x_{fix}, y_{fix}, z_{fix}, and x_{mov}, y_{mov}, z_{mov} be the x, y, and z coordinates of the origin of the fixed and movable jaw in the part coordinate. Because a fixed jaw and a movable jaw are placed face to face as shown in Figure 6-1, $x_{fix} = x_{mov} = x_o$ and $z_{fix} = z_{mov} = z_o$. x_o, y_o, and z_o are the coordinates of the vise jaw's origin.

Let W_{fix} be the width of a fixed jaw and W_{mov} be the width of a movable jaw. Note that the length and height of a jaw L_{jaw} and H_{jaw} are the same for both a fixed jaw and a movable jaw. Let y_{fix} and y_{mov} be the y coordinates of the contact planes for a fixed jaw and movable jaw.

6.7.1. Determining the y Coordinate of the Jaw Origin

As mentioned earlier, the y coordinates of the origin of a fixed and movable jaw can be easily determined by the y coordinate of the contact planes and the width of a fixed and movable jaw.

$y_{fix} = y_{fix} - 0.5\ W_{fix}$ and $y_{mov} = y_{mov} + 0.5\ W_{mov}$.

6.7.2. Determining the z Coordinate of the Jaw Origin

Figure 6-15 shows how the z coordinate of the jaw location, z_o, is determined in the part coordinate. d is used to provide clearance between the jaw and obstacles. When $z^{cf}_{max} > H_{jaw} + d$, there is only one way to determine the z coordinate of the jaw location. That is, $z_o = 0$.

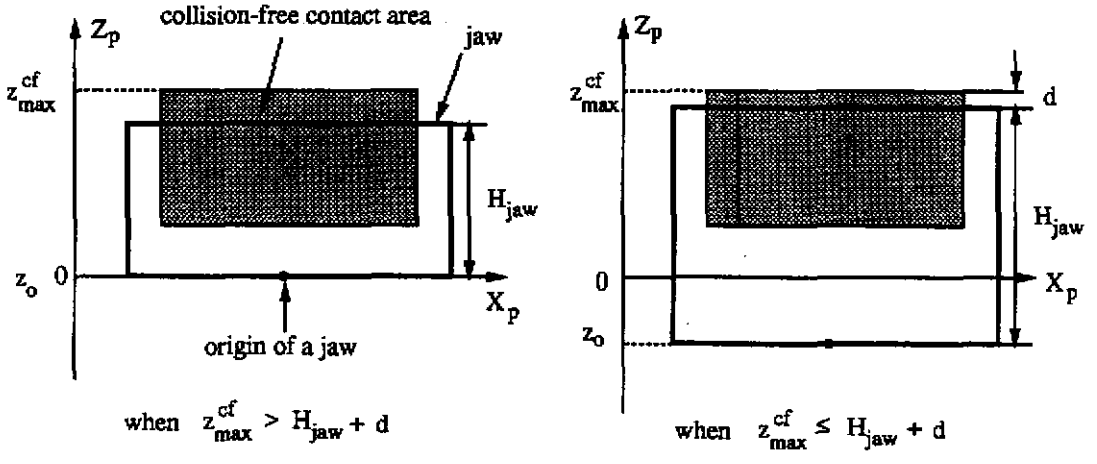


Figure 6-15: Determination of z_o of the jaw location

However, when $z^{cf}_{max} \leq H_{jaw} + d$, many ways exist to place a jaw against the collision-free contact area while having the same contact area between the jaw and the area (see Figure 6-16). In practice, the part is exposed out of a vise to give cutters a better access to the part. Thus, the current reasoning determines the z coordinate of the jaw location so that the top surface of the jaw should not exceed the collision-free contact area That is, $z_o = z^{cf}_{max} - H_{jaw} - d$. Figure 6-17 shows a few examples of the jaw locations along the z axis according to current reasoning when we consider only the part geometry, ignoring the interference from cutter paths.

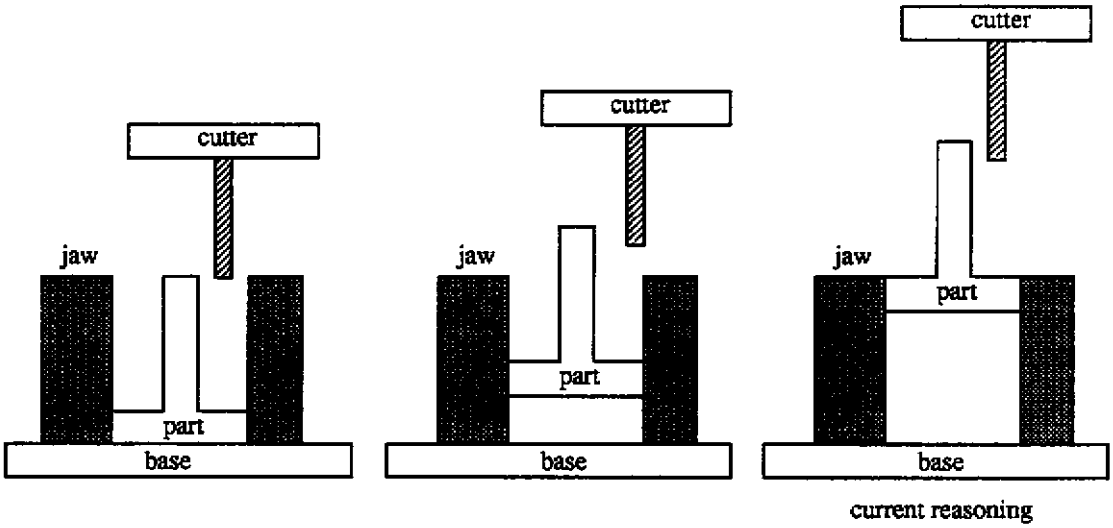


Figure 6-16: Possible part locations against the jaw

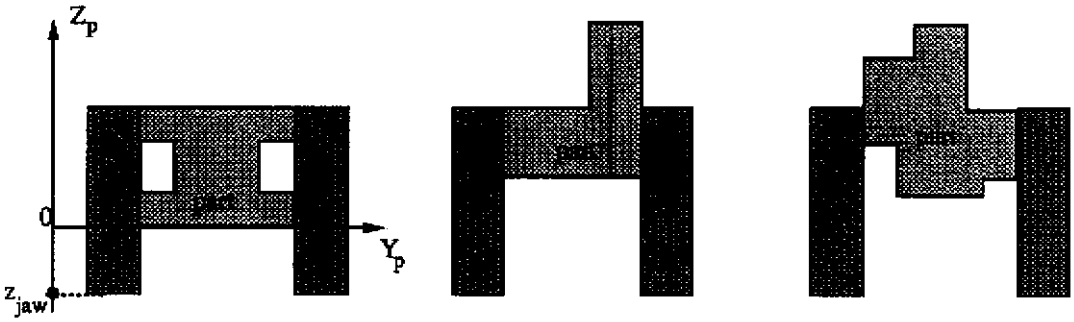


Figure 6-17: Examples of jaw locations along the z axis according to the current reasoning

6.7.3. Determining the x Coordinate of the Jaw Origin

Every collision-free area identified on the common contact area can be categorized into four cases to determine x_o of the jaw location (see Figure 6-18). d is used to provide clearance between the jaw and the obstacles.

For brevity, let L_{cf} be $x^{cf}_{max} - x^{cf}_{max}$. Then, the following reasoning can be used to determine the x coordinate of the jaw origin.

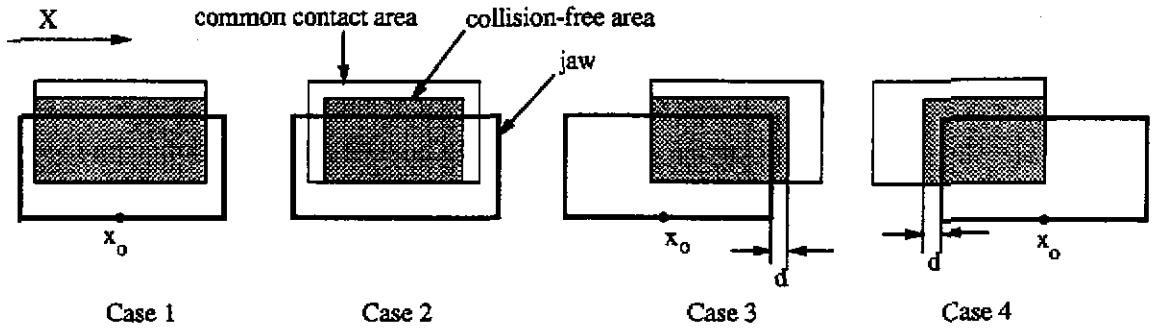


Figure 6-18: Determination of x_o of the jaw location

When $L_{cf} > L_{jaw} + 2\,d$

$x_o = .5\,(x^{cf}_{min} + x^{cf}_{min})$

When $L_{cf} < L_{jaw} + 2\,d$

Case 1: When $x^{cf}_{min} = x^{cm}_{min}$ and $x^{cf}_{max} = x^{cm}_{max}$

$x_o = 0.5\,(x^{cf}_{min} + x^{cf}_{max})$.

Case 2: When $x^{cf}_{min} > x^{cm}_{min}$ and $x^{cf}_{max} < x^{cm}_{max}$

The jaw cannot be placed.

Case 3: When $x^{cf}_{min} = x^{cm}_{min}$ and $x^{cf}_{max} < x^{cm}_{max}$

$x_o = x^{cf}_{max} - 0.5\,L_{jaw} - d$.

Case 4: When $x^{cf}_{min} > x^{cm}_{min}$ and $x^{cf}_{max} = x^{cm}_{max}$

$x_o = x^{cf}_{min} + 0.5\,L_{jaw} + d$.

6.7.4. Adjusting the Jaw Location

In identifying collision-free areas, we have only considered cutter paths that interfere only with the common contact area. Then the x and z coordinate (x_o and z_o) of the fixed jaw and the movable jaw have been determined without considering any other cutter paths. If $L_{cf} > L_{jaw} + 2\,d$, the jaw is placed within the collision-free area. Thus, there is no need to check interference between the jaw and other cutter paths. When $L_{cf} \le L_{jaw} + 2\,d$, cutter paths may interfere with the jaw at the current jaw location.

Any other cutter paths that do not interfere with the common contact area are checked for interference against the jaw geometry. Let x^{obs}_{min}, x^{obs}_{max}, and z^{obs}_{min} be the minimal and maximal x and z coordinates among obstacles.

Case 1: When $x^{cf}_{min} = x^{cm}_{min}$ and $x^{cf}_{max} = x^{cm}_{max}$ (see Figure 6-19)

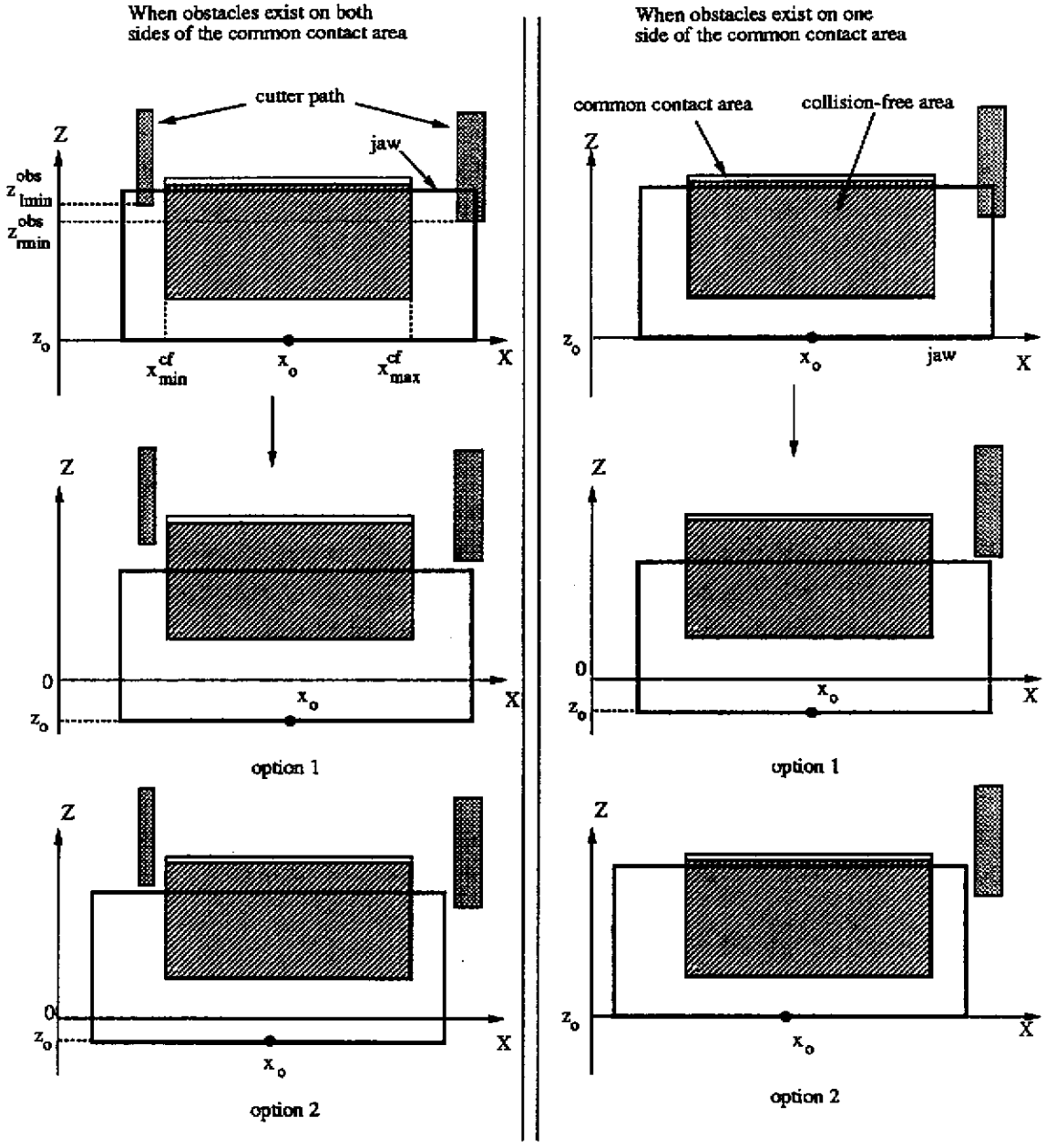


Figure 6-19: Adjusting the jaw location when the entire length of the common contact area along the X axis is accessible to the jaw

<When there are obstacles on both sides of the common contact area>

Let x^{obs}_{rmin} be the minimal x coordinate among the obstacles on the right hand side of the common contact area. Let z^{obs}_{rmin} be the minimal z coordinate of the obstacle with x^{obs}_{rmin}. Similarly, let x^{obs}_{lmax} be the maximal x coordinate among the obstacles on the left hand side of the common contact area. Let z^{obs}_{lmin} be the minimal z coordinate of the obstacle with x^{obs}_{lmax}.

Option 1: adjust the jaw location such that $z_o = z_{min}^{obs} - H_{jaw}$.

Option 2: If $z_{rmin}^{obs} > z_{lmin}^{obs}$, adjust the jaw location such that $x_o = x_{lmax}^{obs} + 0.5\ L_{jaw}$ and $z_o = z_{rmin}^{obs} - H_{jaw}$. Otherwise, adjust the jaw location such that $x_o = x_{rmin}^{obs} - 0.5\ L_{jaw}$ and $z_o = z_{lmin}^{obs} - H_{jaw}$.

If the jaw at the new location interferes with new obstacles, $z_o = z_{min}^{nobs} - H_{jaw}$ where z_{min}^{nobs} is the minimal z coordinate among new obstacles that interfere with the jaw. If $z_{min}^{nobs} > z_{min}^{obs}$, the jaw location is adjusted by option 2 because it provides a larger contact area. Otherwise, the jaw location is adjusted by option 1. If the jaw does not interfere, the jaw location is adjusted according to option 2.

<When there are obstacles on one side of the common contact area>

Option 1: adjust the jaw location such that $z_o = z_{min}^{obs} - H_{jaw}$.

Option 2: If the jaw interferes at the right hand side of the common contact area, adjust $x_o = x_{min}^{obs} - 0.5\ L_{jaw}$. If the jaw interferes at the left hand side of the common contact area, adjust $x_o = x_{max}^{obs} + 0.5\ L_{jaw}$.

If the jaw interferes with new obstacles, $z_o = z_{min}^{nobs} - H_{jaw}$ where z_{min}^{nobs} is the minimal z coordinate among new obstacles that interferes with the jaw. If $z_{min}^{nobs} > z_{min}^{obs}$, the jaw location is adjusted by option 2 because it provides a larger contact area. Otherwise, the jaw location is adjusted by option 1.

If the jaw does not interfere, the jaw location is adjusted according to option 2.

Case 2: **When $x_{min}^{cf} > x_{min}^{cm}$ and $x_{max}^{cf} < x_{max}^{cm}$**

Because the collision-free area is within the common contact area, the jaw does not interfere with any obstacles at all. Thus, the jaw location remains intact (see the second example of Figure 6-18).

Case 3: **When $x_{min}^{cf} = x_{min}^{cm}$ and $x_{max}^{cf} < x_{max}^{cm}$** (see Figure 6-20)

If the jaw interferes with obstacles, $z_o = z_{min}^{obs} - H_{jaw}$. where z_{min}^{obs} is the minimal z coordinate among obstacles that interferes with the jaw.

Case 4: **When $x_{min}^{cf} > x_{min}^{cm}$ and $x_{max}^{cf} = x_{max}^{cm}$** (see Figure 6-20)

If the jaw interferes with obstacles, $z_o = z_{min}^{obs} - H_{jaw}$. where z_{min}^{obs} is the minimal z coordinate among obstacles that interferes with the jaw.

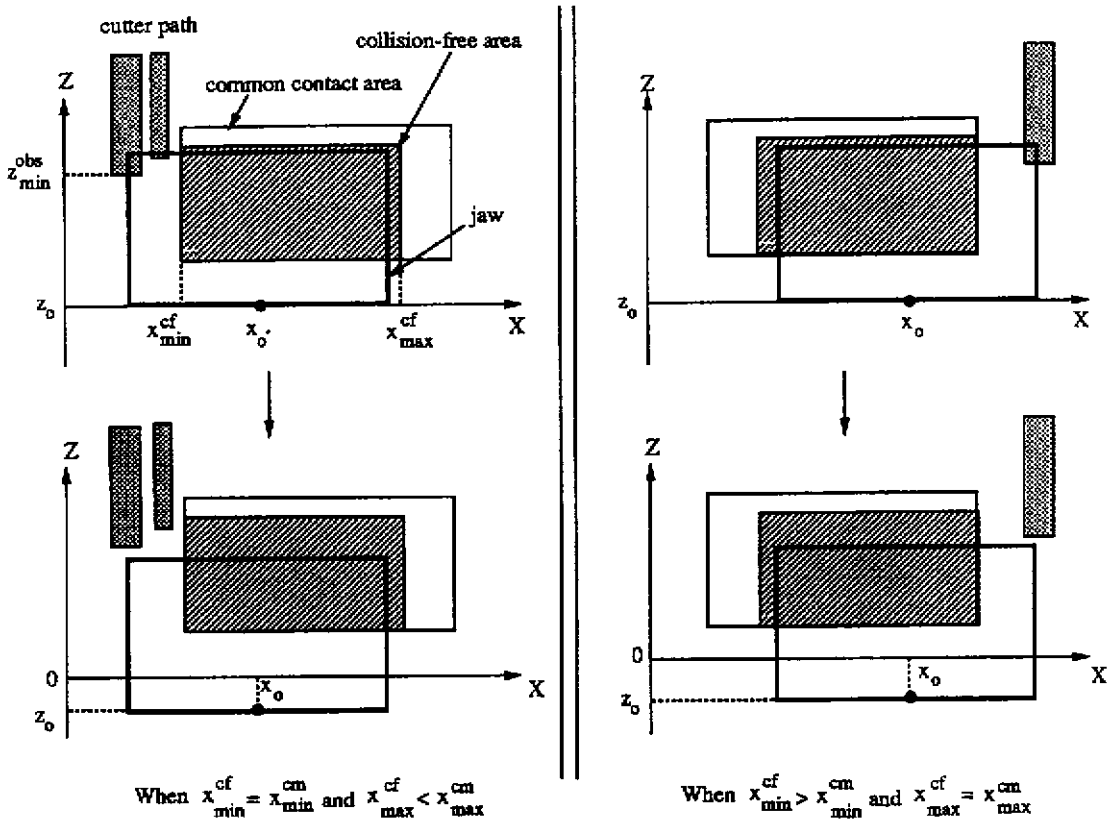


Figure 6-20: Adjusting the jaw location against cutter paths

6.8. Determining the height and location of parallel bars

In order to provide flexibility in achieving the required height of parallel bars, the system assume modular parallel bars. For the practical search space, we also assumes the use of parallel bars with the same length and the same thickness (see Figure 6-21).

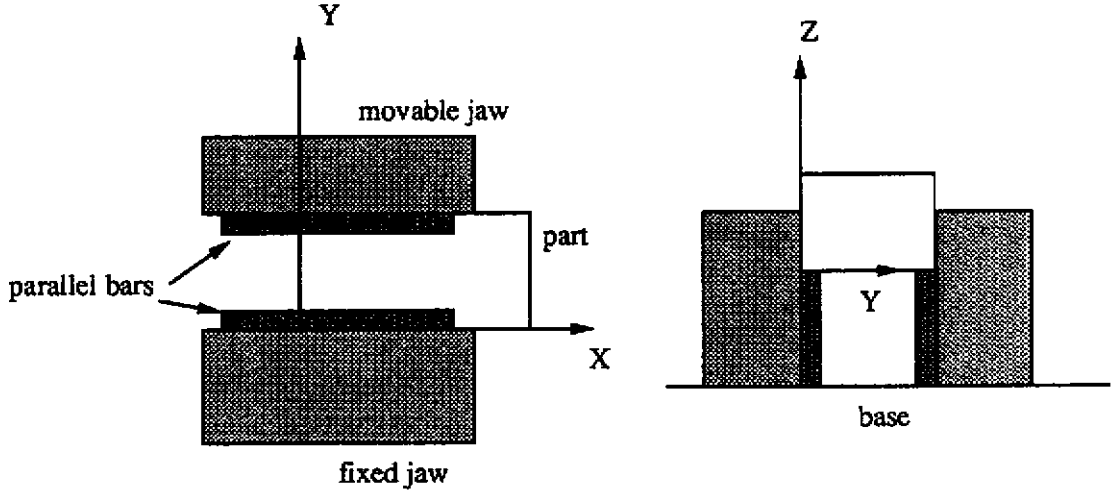


Figure 6-21: Location of parallel bars

Parallel bars should be placed along side each other under the bottom reference surface. Although many ways exist to place parallel bars under the part, parallel bar(s) are typically placed in contact with the jaws. However, the part geometry cannot be placed against the jaws when the part's bottom reference surface does not touch the jaw's surface. In this case, parallel bars should be placed away from the jaws (see Figure 6-22). When the part cannot be supported stably by parallel bars, the fixture plan should not be used. The current reasoning only considers the location of parallel bars when they are placed against jaws and can support the part stably.

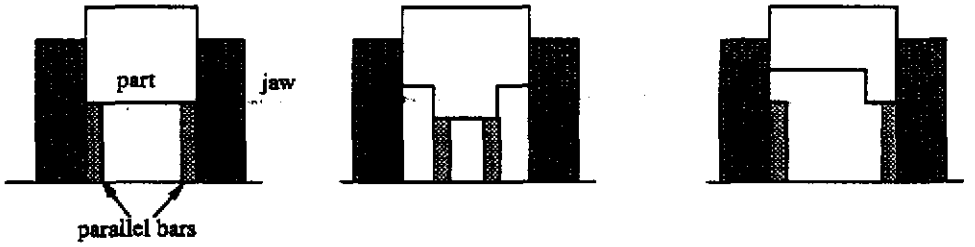


Figure 6-22: Location of parallel bars under various parts

6.8.1. Determining the Height of Parallel Bars

Since parallel bars with the same thickness and length are assumed, it is only necessary to determine their height. Let H_{bar} be the necessary height of parallel bars. Let H_{min} be the minimum height of parallel bars when the part needs to be raised from the base plate. This is typically determined by the clearance between cutter paths and the base plate in order to avoid interference. For example, H_{min} is set to be 0.25" for the current system.

Note that always $z_o \leq 0$ in the part coordinate. The height of parallel bars can be easily determined by taking the absolute value of of z_o. That is, $|z_o|$ corresponds to H_{bar}. Figure 6-23 shows 3 difference cases depending on $|z_o|$ and H_{min}.

Case 1: If $|z_o| = 0$, the part can be supported by the base plate without parallel bars if any cutter paths do not interfere with the base plate. Let z_{min}^{obs} be the minimal z coordinate among swept volumes of cutter paths in the part coordinate.

That is, if $z_{min}^{obs} \leq 0$, $H_{bar} = H_{min}$. Otherwise, parallel bars are not needed ($H_{bar} = 0$). For example, a cutter path for through-holes or end-milling to cut sides may interfere with the base plate.

Case 2: If $|z_o| \geq H_{min}$, $H_{bar} \geq |z_o|$.

When the algorithm determines the height for parallel bars, one or more parallel bars from the library can be selected to provide the necessary height. In reality, it is not always possible to achieve the specified height by the existing parallel bars in the modular fixturing system. Thus the minimum height higher than $|z_o|$ should be used in consideration of available parallel bars. For example, if $|z_o|$ is determined to be

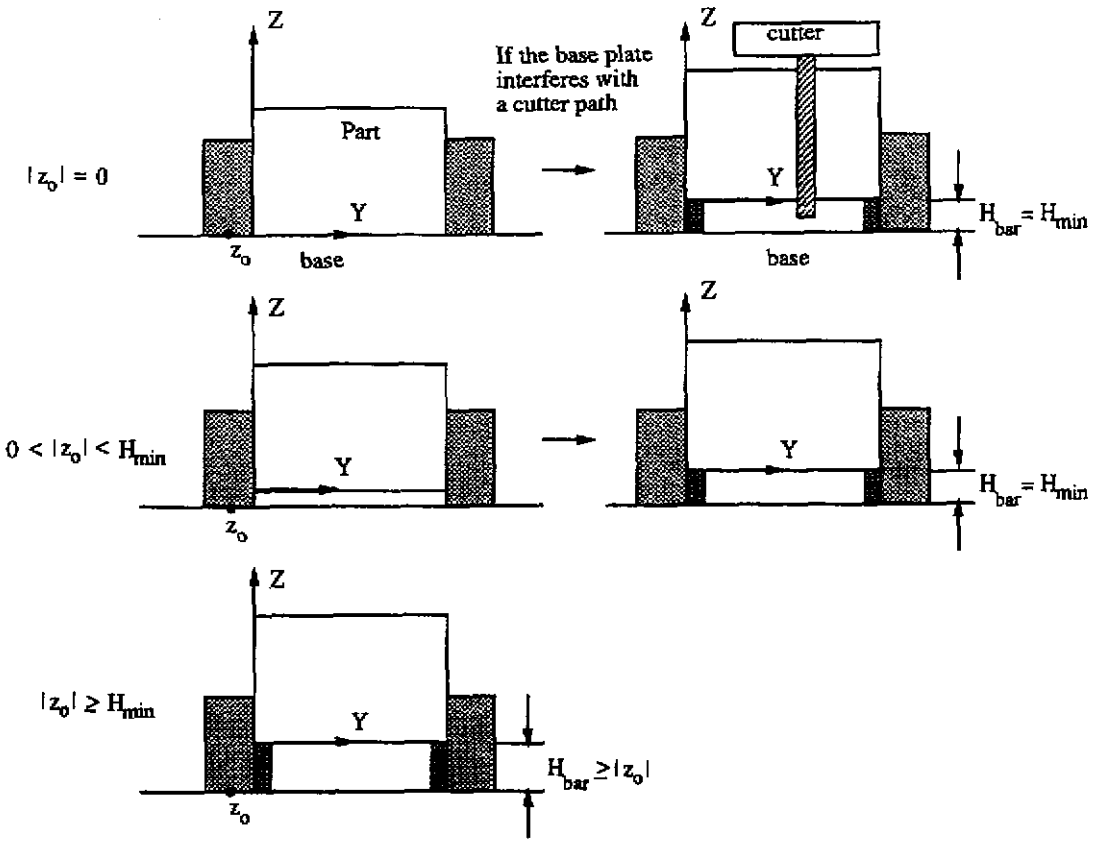


Figure 6-23: Determination of the height of parallel bars

1.15" by the algorithm and the modular fixturing system has a mixture of parallel bars with the height of 0.25", 0.5", and 1", the minimum height greater than 1.15" is 1.25". Thus $H_{bar} = 1.25"$.

Case 3: If $|z_o| < H_{min}$, $H_{bar} = H_{min}$.

Note that in case 2 and 3, there is no need to check interference between the cutter paths and the base plate because the part needs to be raised from the base plate anyway. The z coordinate of the vise jaw needs to be adjusted depending on the actual height of the parallel bars. That is, $z_o = - H_{bar}$.

6.8.2. Determining Location of Parallel Bars

A parallel bar is modeled as a rectangular block. The locations of parallel bars should be determined such that they do not interfere with the cutter paths. While the y and z coordinates of the parallel bars' origin can be determined easily, the x coordinate can be determined by the same reasoning used to determine the x coordinate of the jaw locations (see Figure 6-18). This is possible because we have assumed that a parallel bar is in contact with a vise jaw. Let L_{bar} be the length of the parallel bars. In this reasoning, L_{jaw} needs to be replaced by L_{bar}.

When $L_{cf} > L_{bar} + 2\,d$

$x_{bar} = .5\ (x^{cf}_{min} + x^{cf}_{min})$

When $L_{cf} < L_{bar} + 2\,d$

Case 1: When $x^{cf}_{min} = x^{cm}_{min}$ and $x^{cf}_{max} = x^{cm}_{max}$

$x_{bar} = 0.5\ (x^{cf}_{min} + x^{cf}_{max})$.

Case 2: When $x^{cf}_{min} > x^{cm}_{min}$ and $x^{cf}_{max} < x^{cm}_{max}$

Case 3: When $x^{cf}_{min} = x^{cm}_{min}$ and $x^{cf}_{max} < x^{cm}_{max}$

$x_{bar} = x^{cf}_{max} - 0.5\,L_{bar} - d$.

Case 4: When $x^{cf}_{min} > x^{cm}_{min}$ and $x^{cf}_{max} = x^{cm}_{max}$

$x_{bar} = x^{cf}_{min} + 0.5\,L_{bar} + d$.

For complex cutting operations, parallel bars placed according to the above reasoning may interfere with the cutter paths. For conservative reasoning, the current algorithm rejects the fixture plan when parallel bars interfere with the cutter paths. In the future, this reasoning will be refined to adjust the location in the presence of cutter paths by investigating other possible locations for parallel bars.

6.9. Estimation of the clamping force

In fixture planning with a vise, a tool designer typically determines the clamping force conservatively in order that the part be rigidly held within the vise. The estimation of clamping force is performed based on his past experience rather than using analytical tools. As a result, when the magnitude of the clamping force is too conservative, it may deflect or deform the part when the part is either thin or has concavity. Thus, it is important to estimate the minimal clamping force using a more accurate method in order to reduce part deflection due to clamping force.

The movable jaw applies its clamping force throughout the contact area between the jaw and the part. It is difficult to establish an accurate force model to compute the necessary clamping force because the pressure distribution on the contact area by the movable jaw is unknown during off-line planning. Since our goal is to estimate a conservative clamping force, the force analysis doesn't have to be precise, and the simplified force model can be used. In order to overcome the difficulty of modeling the contact area between the vise and the part, the pressure distribution between a movable jaw and the part is assumed to be uniform over the contact area.

6.9.1. Identifying the Contact Area between Jaws and the Part

The clamping force necessary to hold a part with a vise varies depending on the contact area and cutting force and direction. In order to accurately estimate the necessary clamping force to hold the part rigidly, it is critical to identify the contact area between the jaws and the part.

The jaw is represented as a rectangle parallel to the x axis on the contact plane. The part surface on the contact plane may have multiple faces. Each face that has a contact with the jaw can be identified by using the interference checking algorithm described in Chapter 3. The intersected areas are bounded by a rectangle for simpler geometric reasoning and represents the contact area between the jaw and the part (see Figure 6-24). The contact area is identified for a fixed jaw and a movable jaw, respectively. For conservative analysis, the common area is found by overlapping two contact areas on a plane parallel to both contact planes and is used to estimate the clamping force (see Figure 6-25). Depending on the size of the jaw surface, jaw location, and the part geometry, contact areas may not exist.

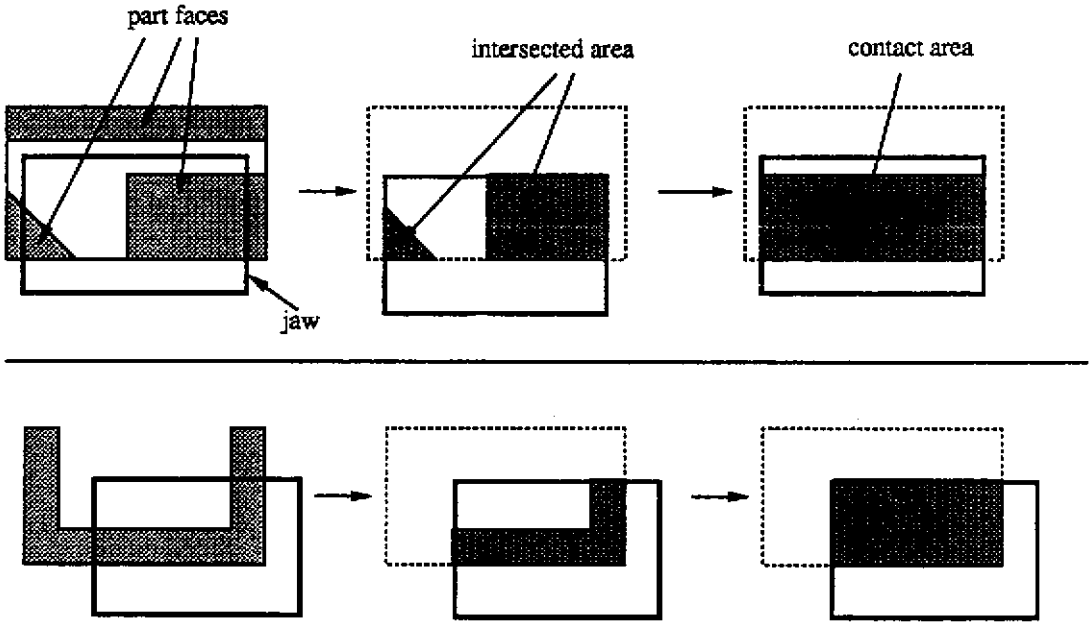


Figure 6-24: Identifying the contact area between the jaw and the part

6.9.2. Estimation of Clamping Force

The pressure distribution from the clamping force is assumed to be uniform over the common area. Three point contacts are used to represent the contact area in order to simplify the analysis, and it is assumed that each contact applies the same clamping force. Thus, the problem becomes identical to the estimation of a clamping force for a fixture plan with 3 overhead clamps. Since the contact area is perpendicular to the base plate, the force analysis is done in 2D by only considering the cutting forces acting on the X-Z plane. For a milling or drilling operation, we have conservatively assumed a cutting force direction parallel to the X-Z plane. (Note that for a drilling operation by a 3 axis milling machine, the cutting force direction is always parallel to the X-Z plane.)

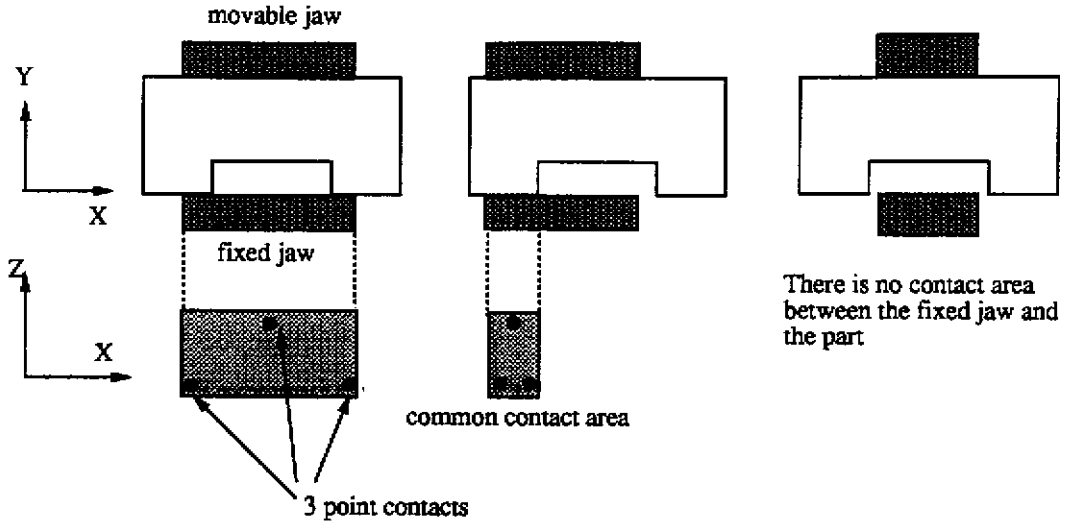


Figure 6-25: The common area used to estimate the clamping force when a part is held by various vises

Figure 6-26 shows the force model used to estimate the clamping force for a fixture plan with a vise. For the conservative estimation of clamping force, the smallest friction coefficient between the part and the vise jaw is used, considering their materials and contact conditions.

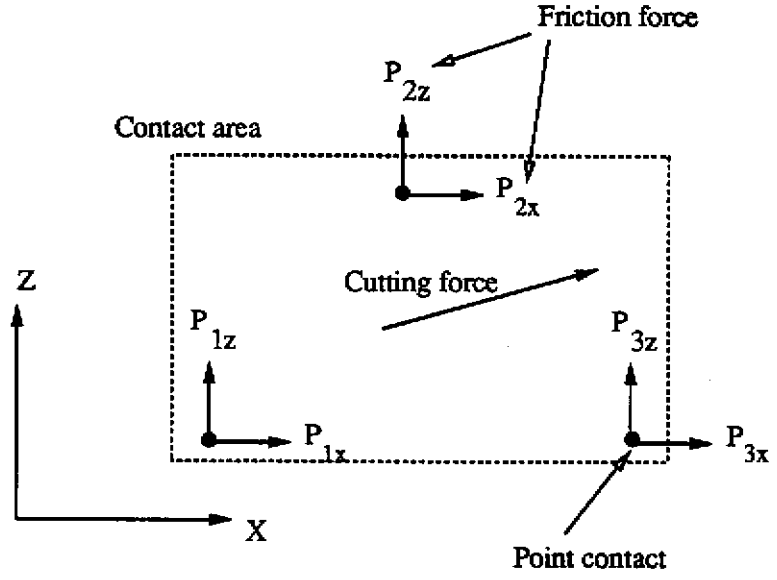


Figure 6-26: A force model to estimate the clamping force for a fixture plan with a vise

The force analysis computes the minimum clamping force to hold the part during machining by considering each cutter force one at a time. The clamping force that a movable jaw should apply to hold the part rigidly is the largest clamping force among the minimum clamping forces.

6.10. Rating Fixture Plans

When more than one fixture plan exists, the plan with the least clamping force is most highly favored, since the problem of unacceptable part deflection due to clamping force may be prevented and the required clamping force has a larger safety margin from the vise's maximal clamp force. Thus, the algorithm rates each plan according to the magnitude of the required clamping force and orders them so that a tool designer can quickly select the most favorable plan in consideration of the part deflection problem and other constraints he/she may consider.

6.11. Remarks

Every fixture plan is not necessarily generated with the same vise type when there are multiple vise types in the fixture library or when there exist fixture plans with its fixed jaw placed against different reference surfaces on the part. Figure 6-27 shows fixture plans generated with two different vise types for the same part. Because a vise type with the least clamping force is tried first in the algorithm, there is no fixture plans with the fixed jaw against the part's side reference on the X-Z datum plane. However, the vise type with the longer jaws can be used to hold the part.

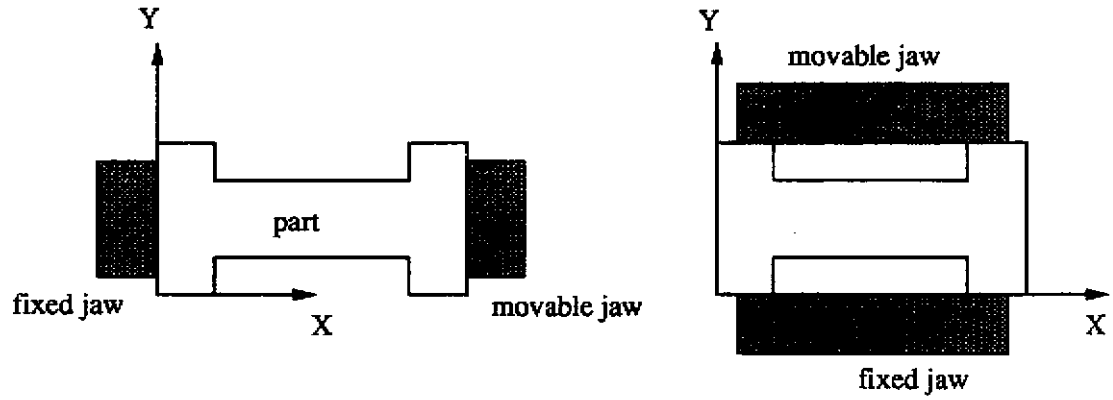


Figure 6-27: Two fixture plans with different vise types

The use of the vise may be limited by the shape of the part and the capacity of the vise since jaws are only allowed to contact a set of parallel surfaces. Since a fixed jaw and a movable jaw are not connected physically in a modular vise, the maximum size of the part that can be held by a vise is only limited by the size of a base plate.

When the part is oriented by a sine plate, the assembly of vise jaws is often difficult unless the assembly can be made in the horizontal position and the sine plate is rotated to the specified angle. When the part needs to be oriented on an angle plate, it could be difficult for a tool designer to locate the part and install the vise jaws in a vertical position. Thus, the algorithm currently does not generate a fixture plan when a part is oriented on either a sine plate with a larger angle than 45^{o} or an angle plate (see Figure 6-28). This assumption can be relaxed when the modular fixturing system allows a tool designer to perform part/vise assembly on a horizontal position.

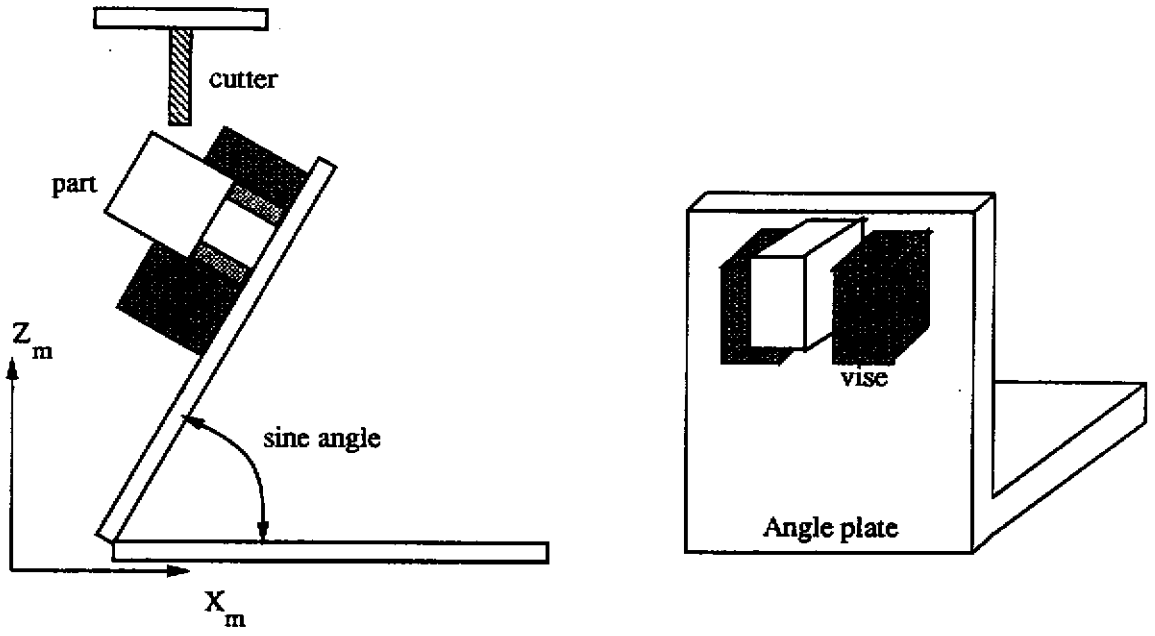


Figure 6-28: Invalid fixture plans on a sine and angle plate

Chapter 7
Implementation and Result

7.1. Introduction

Chapter 4 gave an overview of the system and described the necessary inputs and assumptions in detail. In Chapter 5 and 6, we have described an algorithm and described the reasoning in the various steps to automatically generate fixture plans with overhead clamps or a vise. In this chapter, we describe the implementation of the proposed system and discuss the results.

Section 2 describes the implementation of the system that was built. Section 3 discusses the human interaction required for the system to work in practice. Section 4 discusses the results from some examples for various setups, especially the speed and quality of fixture planning. Some of the results are compared with the fixture plans generated by human experts with or without the aid of a conventional CAD-based fixture planner.

7.2. Implementation

The system is composed of two algorithms that generate fixture plans with a vise and overhead clamps. The algorithm for fixture planning with overhead clamps described in Chapter 5 has been fully implemented in the system. Although the algorithm for fixture planning with a vise described in Chapter 6 have been fully implemented, it may not find every possible collision-free contact area due to the incomplete geometric reasoning.

For interference checking, we have implemented a routine developed to check interference between obstacles and robot arms in robot path planning [Kim 85]. The routine exhaustively checks any interference between every face of two objects until it detects an interference between faces. The limitation is that the routine can deal with only convex polygons. Thus, the routine can deal with any objects as long as their faces are represented by convex polygons. The interference checking routines in the NOODLES' library [Gursoz 91] is known to handle concave polygons also.

For its test bed, the system has been incorporated into the Intelligent Machining Workstation (IMW). The goal of IMW is to automatically and quickly machine a part to specification at the first attempt. IMW consists of the setup planner, the cutting expert, the modeler, the holding expert, and the sensing expert. The system described in this thesis has been implemented as the holding expert (see Figure 7-1). The setup

planner gets cutting plans for a setup from the cutting expert and sends the plans along with the part description and other inputs to the holding expert by way of feature exchange language (FEL). FEL is a language developed at Carnegie Mellon for communication between various experts in IMW [Bourne 88].

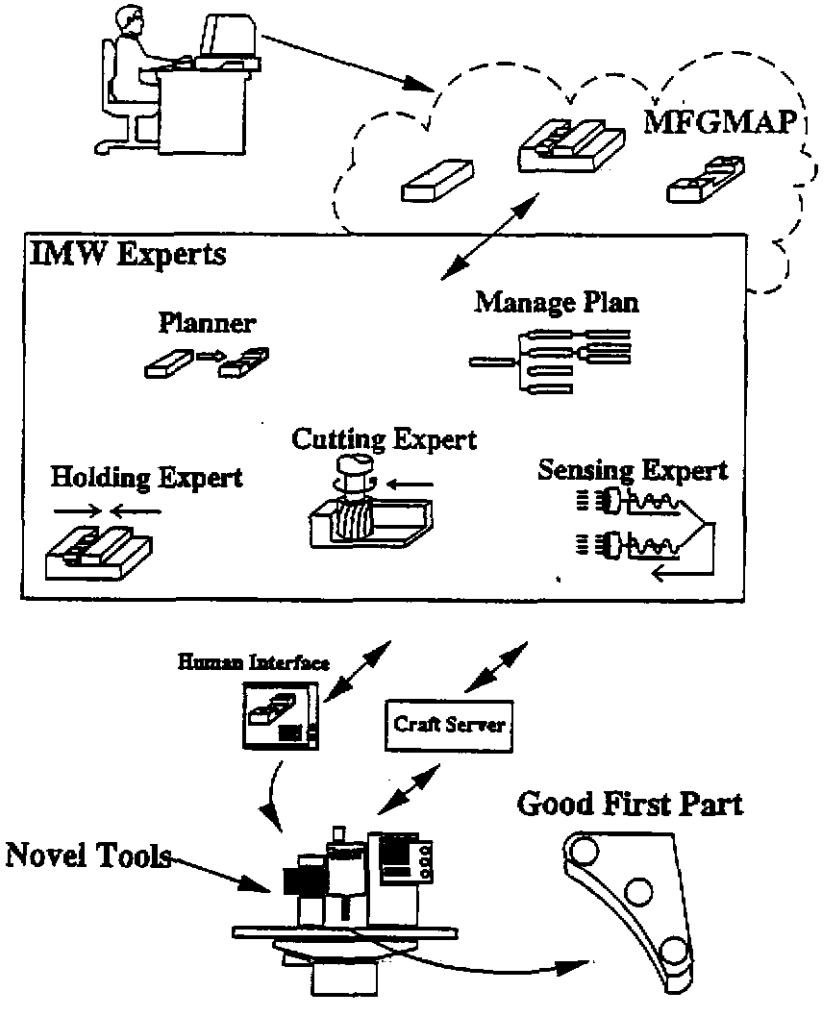


Figure 7-1: Architecture of Intelligent Machining Workstation [Barash 89]

7.2.1. Input Description

To activate the holding expert, the setup planner provides the holding expert with the following inputs - 1) part geometry, 2) part orientation with respect to the machine bed, and 3) cutting plan for each feature.

The details of the inputs considered in the system are described in Chapter 4. Here, we only describe some of the implementation issues related to inputs.

Part geometry

The modeler is based on a solid modeling package [Mashburn 87], and each object is described in constructive solid geometry (CSG) by negating primitive features such as cylinders, etc. from a rectangular block [Bourne 88]. The setup planner sends the holding expert the dimension of the rectangular block and the dimension and location of the primitive features by FEL. The holding expert sends the same FEL messages to the modeler and receives the part geometry in boundary representation (B-rep). Figure 7-2 shows an example of FEL sent from the holding expert to the modeler to construct a part geometry.

As mentioned in Chapter 4, there are two kinds of part geometry to be considered to generate fixture plans with overhead clamps: pre-machined part geometry and post-machined part geometry. The holding expert currently considers only the pre-machined part geometry. As a result, the algorithm for fixture planning with overhead clamps may generate invalid fixture plans when overhead clamps are placed on the region to be removed after machining. These fixture plans can be easily identified by the human expert during the selection of fixture plans. The future implementation of the system will consider both part geometries to avoid the problem.

Cutting plan

A cutter path is described by coordinates of the start and finish points in the part coordinate, cutter diameter, and magnitude of cutting force and torque. Figure 7-3 shows FEL sentences received by the holding expert from the cutting expert to machine three contour features to make the part shown in Figure 7-2.

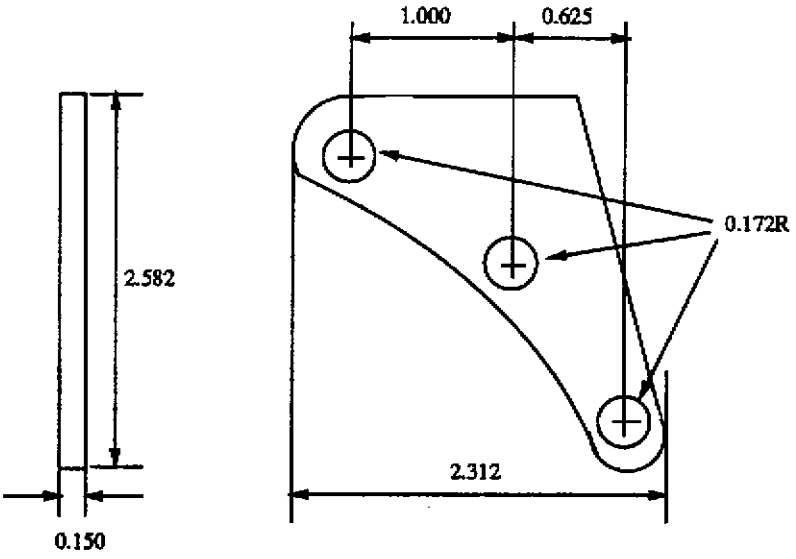
Friction

Since a fixture plan using overhead clamps and a vise relies on friction to hold the part, the friction coefficient value between the part and the fixture components is critical in estimating the necessary clamping force. The friction coefficient may drastically vary depending on the material of the part and fixture components and the contact conditions. For example, aluminum parts have a larger friction coefficient than steel parts. Since cutting fluid during machining reduces the friction coefficient, a conservative value should be used in planning. In the current system, the friction coefficient between the part and fixture components is assumed to be 0.1 for steel parts and 0.2 for aluminum parts.

Fixture library

As explained in Chapter 4, the geometry of the primary fixture elements in a modular fixturing system is simplified to polyhedra while keeping the critical dimensions and stored in various fixture data bases. A detailed description of the fixture components can be stored in another data base and used if a more realistic display is desired.

Currently, the fixture library does not have a complete data base for any particular fixturing system. For demonstration purposes, we have considered a few standard clamps, locators, and supports that could be found in a typical machine shop.




```
; IMW Test Part 2  -- boomerang setup 3
(add ((type application) (name app1))
     ((type environment) (name env1))
; define raw stock
     ((type object)(name obj1)
        (p_vector (0. 0. 0.))
        (w_vector (2.312 0. 0.))
        (l_vector (0. 2.65 0.))
        (d_vector (0. 0. .15))
     )
; define features
     (  (type thru_hole) (name hole1) (object obj1)
        (p_vector (.375 2.207 0.))
        (d_vector (0. 0. .15))
        (radius .172))
     (  (type thru_hole) (name hole2) (object obj1)
        (p_vector (1.375 1.312 0.))
        (d_vector (0. 0. .15))
        (radius .172))
     (  (type thru_hole) (name hole3) (object obj1)
        (p_vector (2. .312 0.))
        (d_vector (0. 0. .15))
        (radius .172))
     (  (type thru_slot) (name short_slot) (object obj1)
        (p_vector (0 2.582 0))
        (w_vector (2.5 0 0))
        (l_vector (0 8 0))
        (d_vector (0 0 .15)))
     (  (type thru_slot) (name angle1) (object obj1)
        (p_vector (2.312 .312 0.))
        (w_vector (1. 0. 0.))
        (l_vector (-.507 2.582 0.))
        (d_vector (0. 0. .15))) )
```

Figure 7-2: Part drawing and FEL of the part geometry delivered by the setup planner

```
(plan ((type setup1)(name plan1)
       (part obj1)(application app1)(environment env1)
       )

; Cut a left top corner contour
      ((type tool_path)(name sweep1)
       (rapid (.4 2.7 -.2))
      )
      ((type tool_path)(name sweep1)
       (force 100)
       (torque 0)
       (diameter .5)
       (radius .5)
       (center (.4 2.2 0))
       (circular (-.1 2.2 -.2))
      )

; Cut a right lower corner contour
      ((type tool_path)(name sweep2)
       (rapid (1.5 .3 -.2))
      )
      ((type tool_path)(name sweep2)
       (force 100)
       (torque 0)
       (diameter .5)
       (radius .5)
       (center (2 .3 0))
       (circular (2.5 .3 -.2))
      )

; Cut a large contour

      ((type tool_path)(name sweep3)
       (rapid (-2. 2.25 -.2))
      )
      ((type tool_path)(name sweep3)
       (force 100)
       (torque 0)
       (diameter .5)
       (radius 3.75)
       (center (-2.0 -1.5 0))
       (circular (1.75 -1.5 -.2))
      )
)
```

Figure 7-3: An example of FEL for cutting plans delivered by the setup planner

For a clamp library, we have considered three different types of strap clamps with the maximum of 4 clamps for each type. Each clamp type has a capability of applying maximum clamping force of 1200, 800, and 400 lb respectively. The clamp size gets smaller with the smaller clamping force. Locators and supports of various heights are stored in a data base.

For a vise library, we have considered two types of vises. Each vise type has a capability of applying a maximum clamping force of 4000 and 2500 lb respectively. We have assumed that the height of a specified parallel bars can be achieved by stacking up multiple modular bars.

7.3. Human Interaction

As discussed in Chapter 3, part deflection checking can be done better by a human expert than by an analytical method due to uncertainty in the force model and difficulty in evaluation. Therefore, the proposed system requires interaction from a human expert to inspect the part deflection problem.

A modular fixturing system may not prevent part deflection due to cutting force depending on its magnitude/direction and the part geometry. In order to make the proposed system effective, a human expert should inspect the input before generating fixture plans to detect such cases. If undesirable part deflections due to cutting forces cannot be prevented by fixture plans with overhead clamps or a vise, a human expert should advise the setup planner to modify the current setup sequence or use a dedicated fixture. The finite element method (FEM) may be used to help a human expert evaluate the part deflection and make a proper decision.

If the human expert does not detect part deflection problems due to cutting forces, the system looks for fixture plans with both a vise and overhead clamps. Depending on the input, both types of fixture plans often exist with more than one plan. While the number of fixture plans with a vise is usually small, the number of fixture plans with overhead clamps can be large.

The human expert prefers a fixture plan with the least clamping force unless it has other problems because these plans are less prone to part deflection and have a larger safety margin for clamping forces. To speed up the human expert's activity, the system rates the fixture plans according to their clamping force. The less the clamping force, the higher the plan is rated.

For each fixture type, the human expert displays the simulated part/fixture assembly of a highly rated fixture plan to see if there is any problem with part deflection and other constraints. If the part needs to be raised from the base plate in a fixture plan with overhead clamps, the algorithm selects an appropriate support from a fixture library and places it underneath each clamp if the part geometry permits. If supports cannot stably support the part, the fixture plan issues a warning message for the human expert to add more supports. The human expert should consider the part deflection problem in determining the number and locations of supports. For example, a certain number of supports (possibly four) can be used to prevent part deflection by placing them at different locations so that they support the part stably. If the part is supported by the base plate or raised by the parallel bars in the fixture plan with a vise, it is assumed that the fixture plan completely support the part.

FEM can be used to automate the evaluation of part deflection. If supports may not prevent the part deflection on the part's resting surface, a subplate can be used as an alternative. If the part is not stably supported by the supports, the human expert may add supports to prevent part deflection. Sometimes, a subplate may be used instead of multiple supports. For example, when installing through-holes in a thin part, a subplate is typically better than multiple supports to prevent part deflection. If the fixture plan does not have any problem, the human expert selects it as the most favorable fixture plan among multiple fixture plans. Otherwise, he/she should view other fixture plans until he finds a trouble-free fixture plan.

7.4. Examples of Fixture Plans

In order to demonstrate the capability of the system, various independent setups have been used. All of the fixture plans has been automatically generated from the system without any human intervention. Since the part deflection problem does not exist, each fixture plan can be implemented.

When a part needs to be raised from the base plate, the system tentatively places supports with equal height underneath each clamp. If the part cannot be stably supported, it is necessary to add more supports or use a subplate during the assembly. If part deflection is unpreventable, a fixture plan cannot be used.

A fixture plan generated by the system is composed of the necessary fixture components, their locations (position and orientation in the part coordinate), and instructions for assembly (see Figure 7-4). The assembly instructions include assembly sequence, clamping force, and any other cautions that the human expert should consider to complete a fixture plan during the assembly. The current system displays the simulated fixture plan using simplified geometries of fixture components in order to speed up the display. For a realistic view of a fixture plan, detailed geometry of fixture components can be used, if desired.

Typically, risers are needed to raise the clamp to the height determined by the algorithm. When available risers in the fixture library are known, selecting appropriate risers is not a difficult task. Markus and et al. [Markus 84] have developed an expert system to build towers to raise the part and clamps to the specified height. Currently, clamps in a fixture plan are displayed while assuming that a riser under each clamp can be integrated into the simplified clamp geometry.

Although simulated fixture plans have been actually displayed on a Silicon graphics terminal in solid models with colors to give a realistic view, we only provide wire frame views in this thesis.

Each example setup is shown with the finished part geometry, selected fixture components positioned according to the fixture plan. Each fixture plan is shown in from an angular view and a top view in order to better understand the simulated part/fixture assembly. Inverted L-shaped polyhedra represent clamps. Large rectangular blocks represent modular vise jaws in which a thinner block represents a movable jaw applying clamping force. Small rectangular blocks represent locators placed according to the 3-2-1 locating rule. Supports and parallel bars are not shown on purpose in order to provide a less congested view. Although the system tentatively places a support under the part at the location of each clamp when the part needs to be raised from the base plate, a tool designer may use a subplate instead to provide better support.

```
*** Plan with clamp type with 500 lb ***

ATTENTION: Part needs to be raised by 0.5 inch from the base plate.
Minimum Clamping force = 155 lbf

            X       Y       Z     Orient      Remark
-------------------------------------------------------------
Support    0.50    5.40    0.00             H= 0.50   D=1.00
Support    0.50    1.40    0.00             H= 0.50   D=1.00
Locator    0.38   -0.25    0.00             H= 1.00   D=0.50
Locator    3.63   -0.25    0.00             H= 1.00   D=0.50
Locator   -0.25    5.63    0.00             H= 1.00   D=0.50

        Part loading

Clamp      0.50    5.40    2.50      0.0    Not extended
Clamp      0.50    1.40    2.50      0.0    Not extended

REMARK: Place fixture components in sequential order.


*** Plan with vise type with 2500 lb along X-Z plane ***

   Clamping force =   1200 lb
   Parallel bar's hgt=    1.00 inches
   Distance from the left end of jaw to part zero =   0.00 inches
   Distance between jaws =   6.00 inches
```

Figure 7-4: Instructions for assembly of fixture plans for Example setup 3

In order to help readers understand figures drawn in lines without depth perception, clamps and vises are shaded with a light gray and locators are shaded darker.

7.4.1. Example setup 1: A rectangular block with a large hole

The dimension of the part is 6 inches in height, width, and length. In this setup, the top surface of the part needs to be face milled and two through-holes also need to be drilled. For each drilling operation, the thrust is assumed to be 120 lb and the torque 100 lb-in. For the face milling operation, a cutting force of 200 lb is assumed.

The system has generated multiple fixture plans with either overhead clamps or a vise. Figure 7-5 shows two sample fixture plans with overhead clamps. The system has selected the clamp type with 800 lb force from the library and placed 4 clamps within the hole. The base plate directly supports the part. The system has estimated the least clamping force to be 625 lb for both plans.

Figure 7-6 shows two fixture plans with a vise. The system has selected the vise type with 2500 lb force from the vise library and has estimated the least clamping force to be 1200 and 1252 lb respectively. Since the part is taller than the vise height and there is no cutting operation that interferes with the base plate, parallel bars are not necessary in both plans.

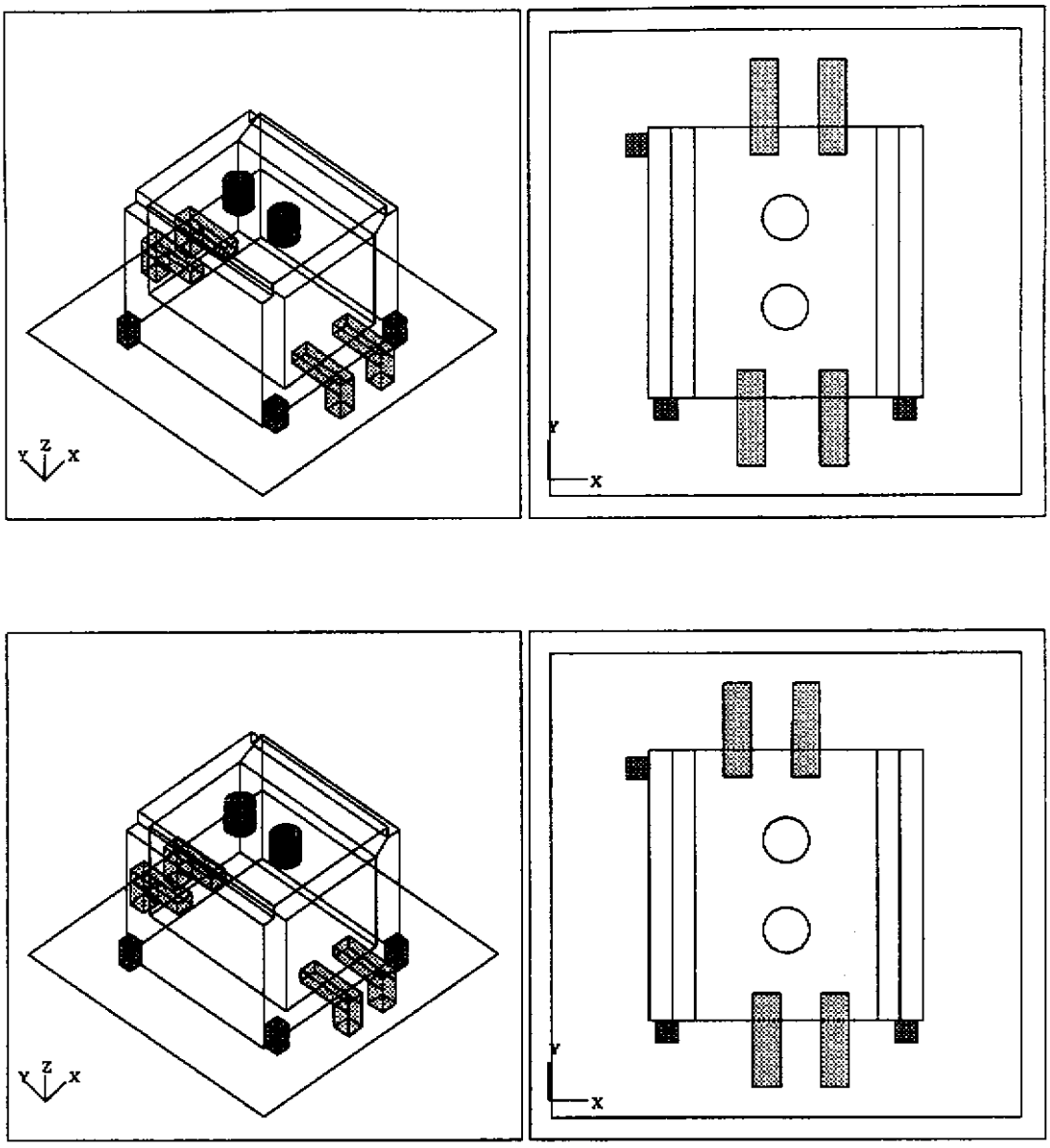


Figure 7-5: Fixture plans with overhead clamps for Example setup 1

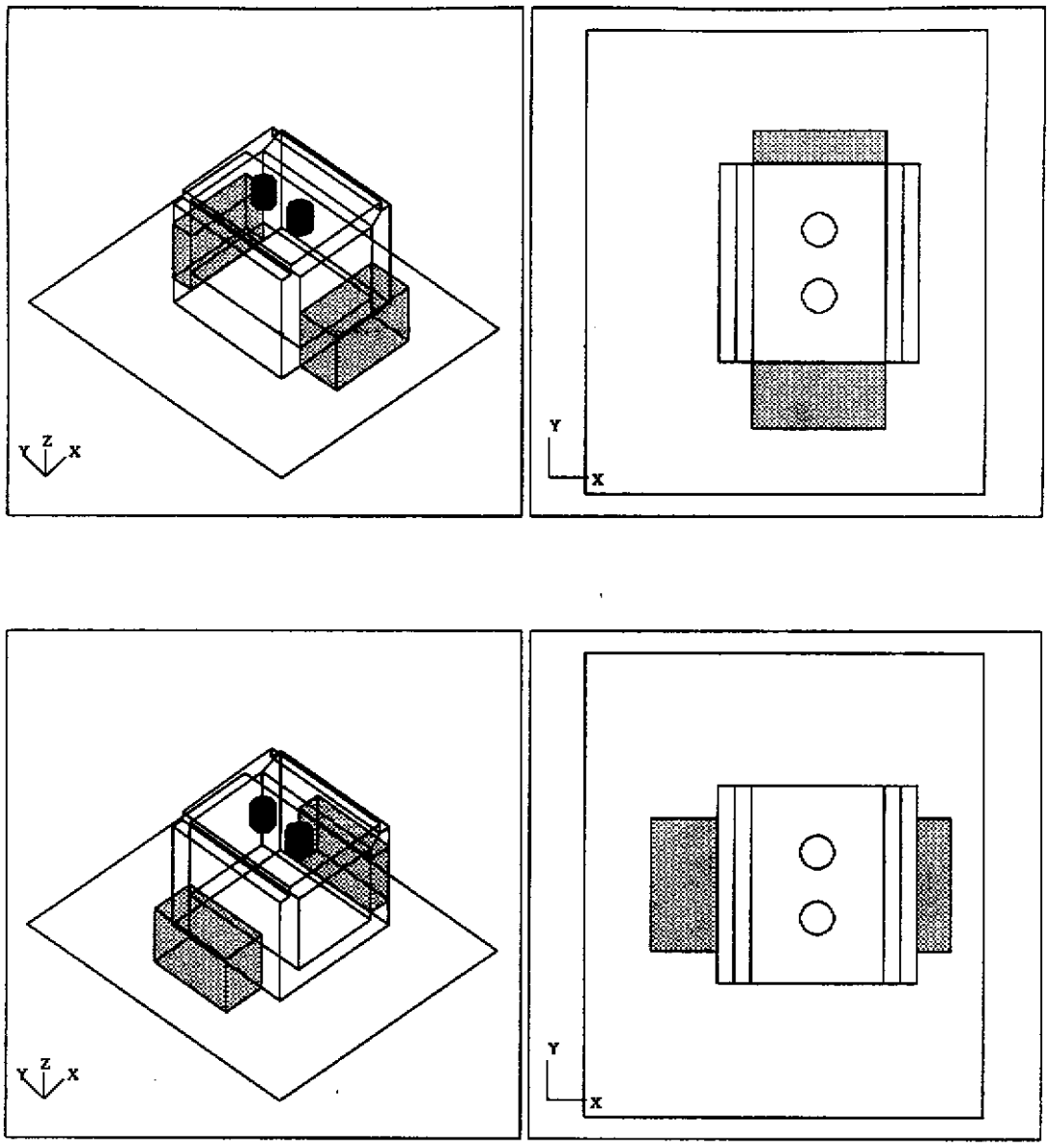


Figure 7-6: Fixture plans with a vise for Example setup 1

7.4.2. Example setup 2: A rectangular block two large slots

The dimension of the part is 6 inches in height, width, and length. This setup requires a face milling operation on the top surface of the part, end milling to make a slot and drilling 4 through holes. Face milling operation is assumed to apply cutting force of 500 lb. For each drilling operation, the thrust is assumed to be 120 lb and the torque 100 lb-in.

The system has generated multiple fixture plans with either overhead clamps or a vise. Figure 7-7 shows two sample fixture plans with overhead clamps. The system has selected the clamp type with 1200 lb clamping force from the library and placed 3 clamps within slots. The base plate directly supports the part. The system has estimated the least clamping force to be 833 lb for both plans.

Figure 7-8 shows two fixture plans with a vise. The system has selected the vise type with 2500 lb force from the vise library and has estimated the least clamping force to be 1274 and 2057 lb respectively. Since the part is taller than vise height and there is no cutting operation that interferes with the base plate, no parallel bars are not needed in both plans.

7.4.3. Example setup 3: A C-shaped part

The dimension of the part is 6 inches in width and length, and 2 inches in height. This setup requires drilling 4 through-holes. For each drilling operation, the thrust is assumed to be 120 lb and the torque 100 lb-in.

The system has generated multiple fixture plans with either overhead clamps or a vise. Figure 7-9 shows two sample fixture plans with overhead clamps. The system has selected the clamp type with 1200 lb clamping force from the library and placed 2 clamps. The system has estimated the least clamping force to be 125 and 132 lb respectively. The part is raised by supports placed under each clamp in order to avoid machining base plate. A tool designer needs to add one or two additional supports to provide better support.

Figure 7-10 shows two fixture plans with a vise. In the first plan, the system has selected the vise type with 2500 lb force from the vise library and has estimated the least clamping force to be 1200 lb. In the second plan, the system has selected the vise type with 4000 lb force and has estimated the least clamping force to be 1800 lb. (Due to the large slot in the part, the system preferred the larger vise.) For eithe plans, parallel bars are needed to raise the part from the base plate.

7.4.4. Example 4: A thin rectangular part on an angle plate

The dimension of the part is 5 inches in width, 3 inches in length, and 0.6 inches in thickness. In this setup, a thin part is oriented by an angle plate. This setup requires a face mill operation on the top surface of the part and end mill operations to cut two slots. Face milling and end milling operation is assumed to apply cutting force of 200 lb.

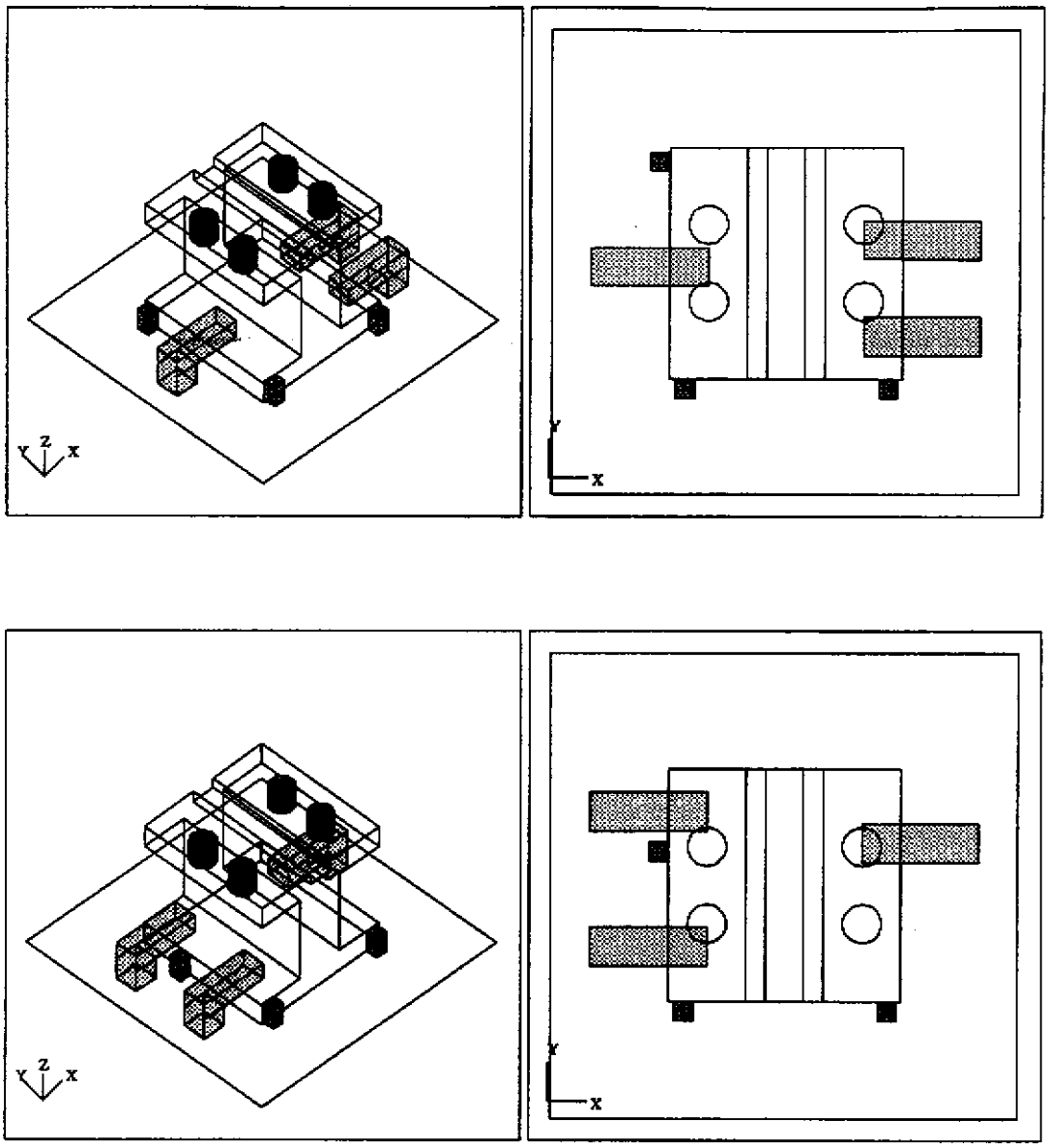


Figure 7-7: Fixture plans with overhead clamps for Example setup 2

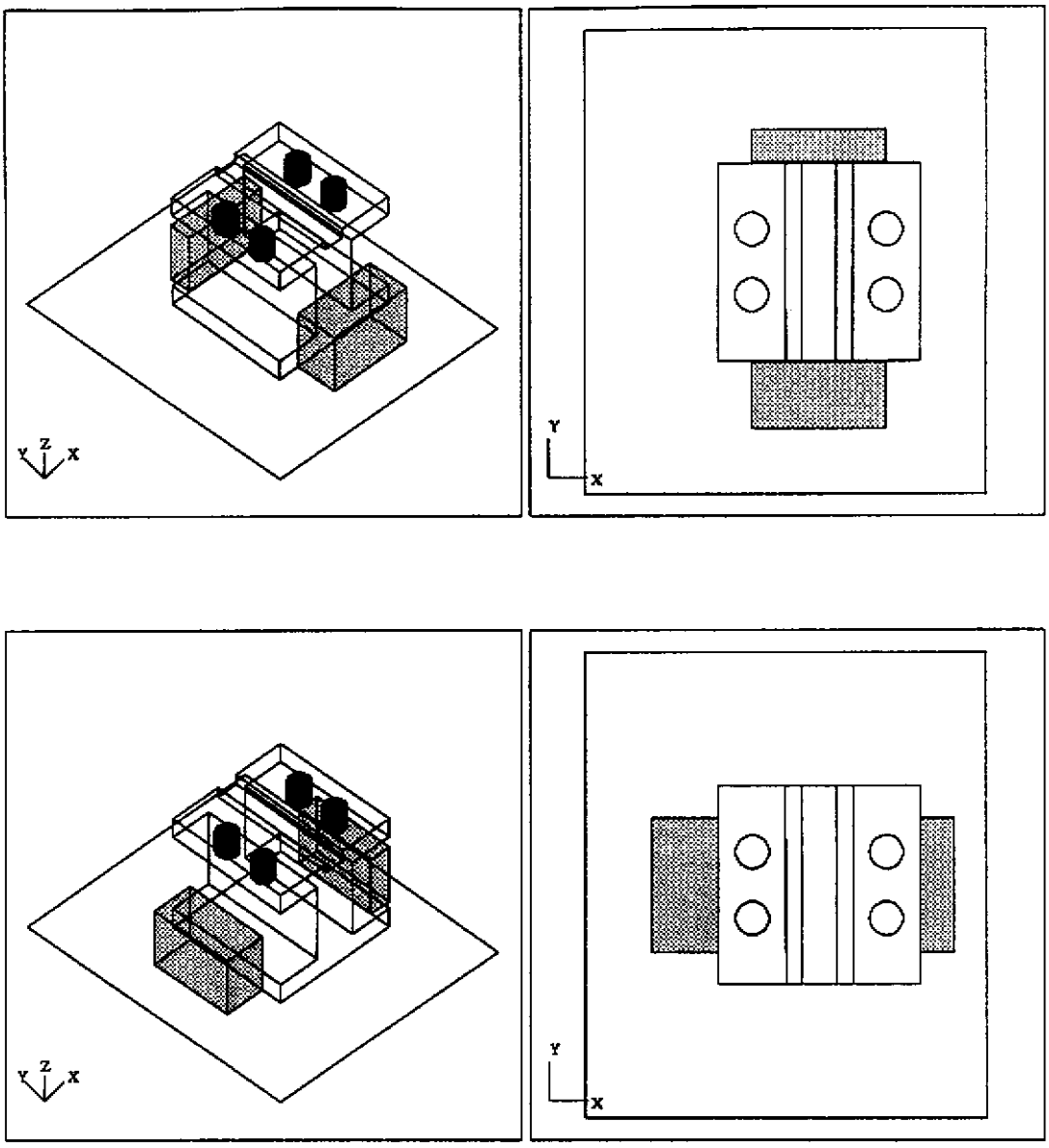


Figure 7-8: Fixture plans with a vise for Example setup 2

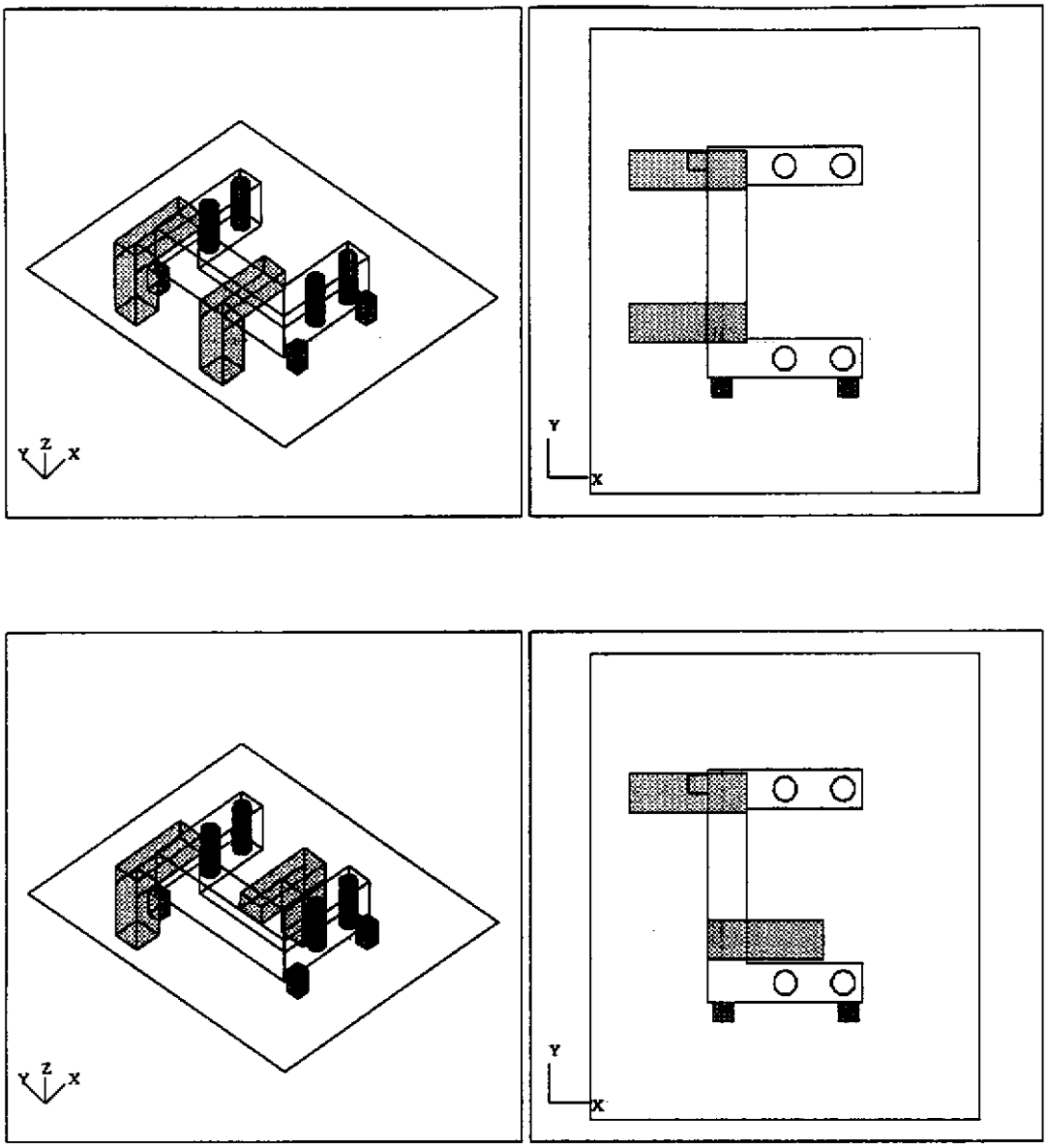


Figure 7-9: Fixture plans with overhead clamps for Example setup 3

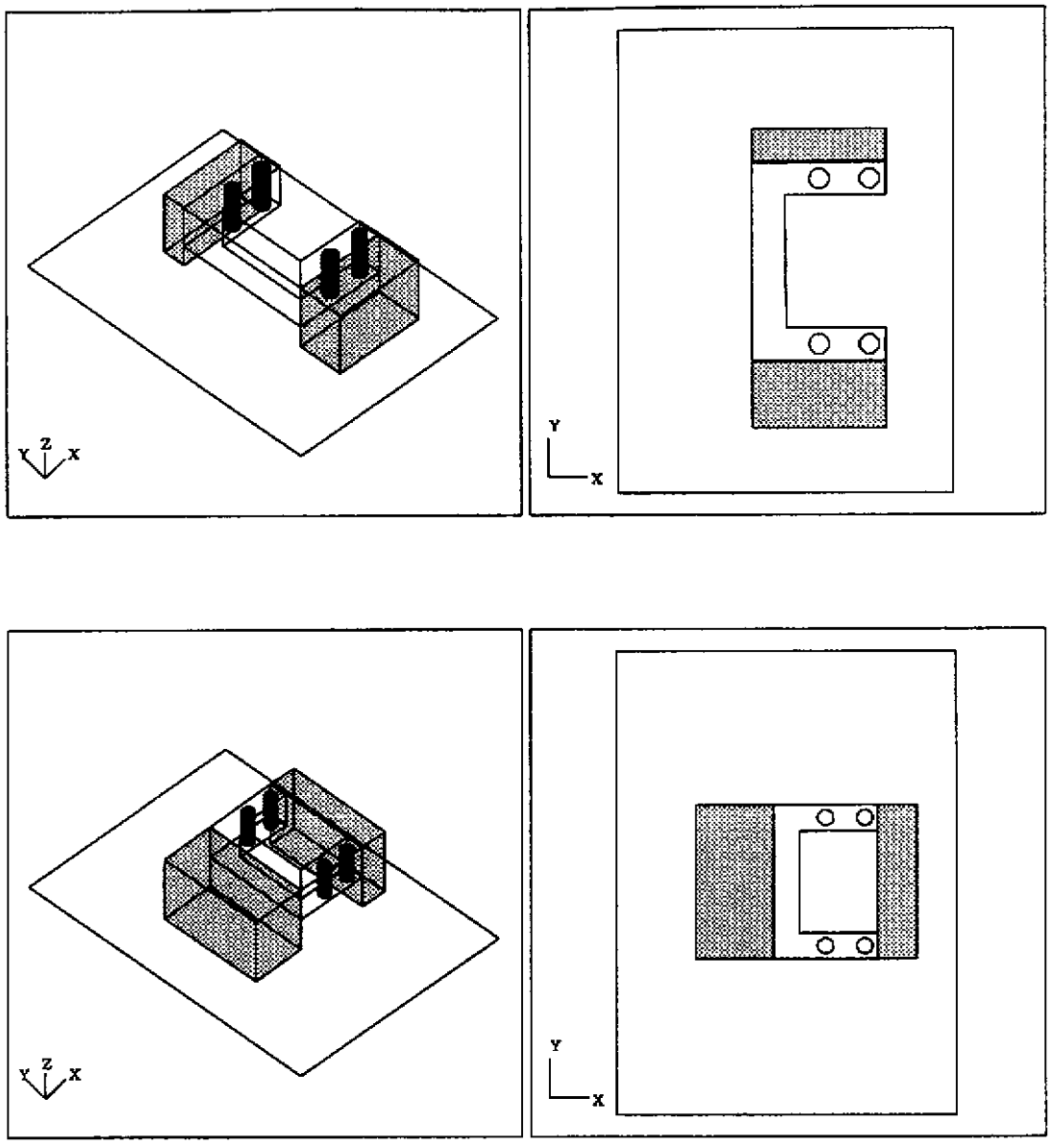


Figure 7-10: Fixture plans with a vise for Example setup 3

The system has generated multiple fixture plans with overhead clamps. Figure 7-11 shows two sample fixture plans with overhead clamps. The system has selected the clamp type with 1200 lb clamping force from the library and placed 2 clamps. The system has estimated the least clamping force to be 300 lb for both plans. The part is directly supported by a base plate and overhangs the angle plate in order to avoid interference between the cutter paths and the base plate. Since the system only considers 3-2-1 locating, a fixture plan with a vise is not generated.

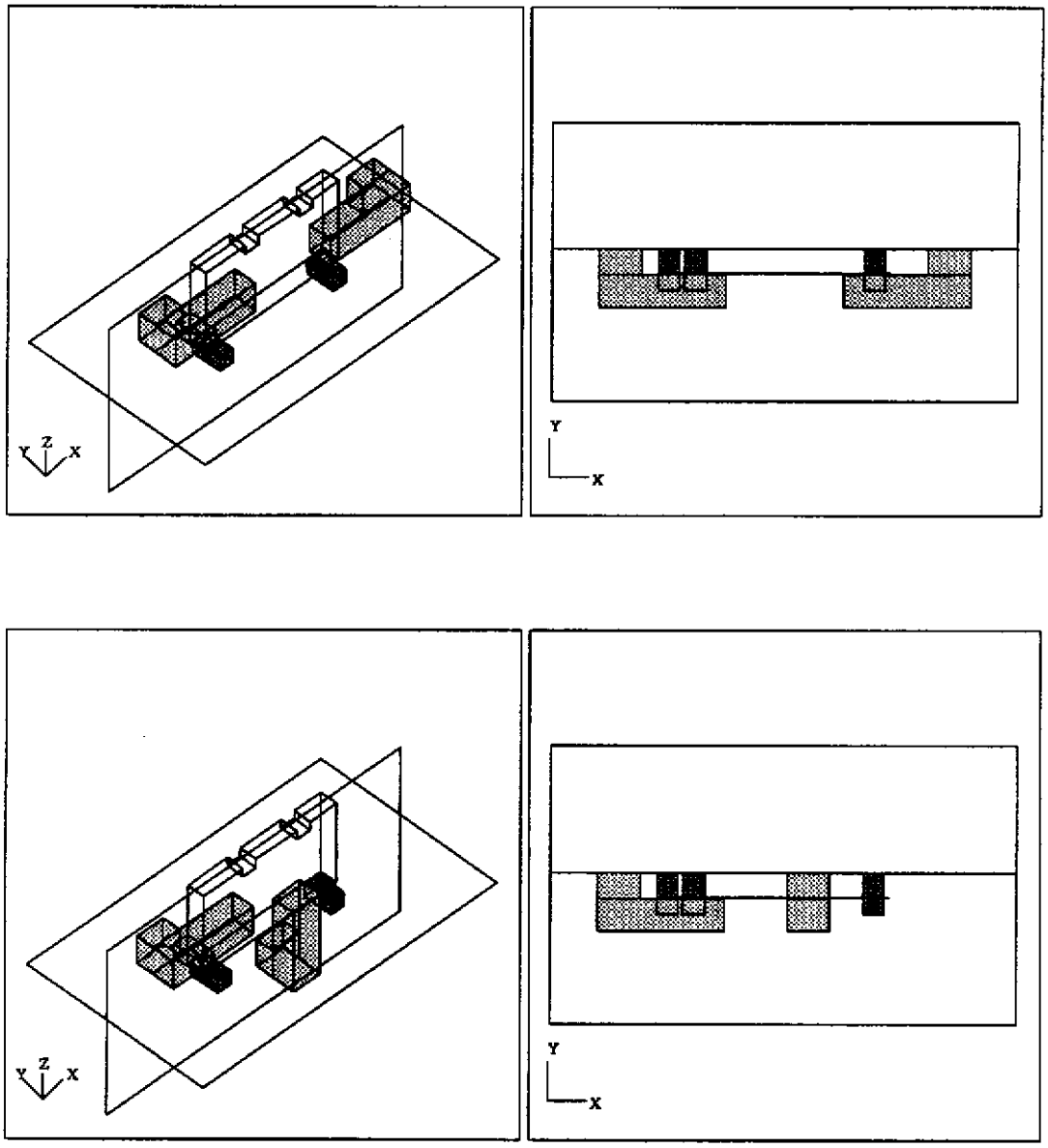


Figure 7-11: Fixture plans with overhead clamps for Example setup 4

7.5. Examples: Fixture Plans for Test Parts

We have used two small parts that are engine brackets in an aircraft. Since these parts are small in size, it is difficult to generate fixture plans for a setup. We have already generated a sequence of setup plans and cutting plans for these parts in IMW. The goal is to see if the system can generate suitable fixture plans for each setup. For brevity, we only show the simulated part/fixture assembly for each setup without giving the details of the fixture plans.

7.5.1. Example 1: Double Chamfer Part

Figure 7-12 shows a part geometry of an engine bracket and manufacturing features. Note that two through-holes need to be chamfered on the opposite side of the slot. Also note that 2 chamfers can be made by end mill operation in the same setup since they are at a right angle, and the part needs to be oriented by the sine plate with the angle 25.5^{o} about the y axis. Because of the constraints from the features, at least 3 setups are required to make the part.

We have used a sequence of setup plans generated by the MACHINIST [Hayes 91]. In the first setup, the top surface needs to be face milled, a slot needs to be end milled, and two holes need to be drilled and threaded. In the second setup, the part is turned over, a side is end milled to size, and two holes are chamfered. In the last setup, the part needs to be oriented by a sine plate with a 25.5 degree angle to make both chamfers by end mill operations. Appropriate cutting plans have been generated for every setup.

The system has only generated fixture plans with a vise for the first setup because clamps cannot be placed on the part due to cutter paths. For the second and third setups, the system has generated fixture plans with a vise and fixture plans with clamps.

In a fixture plan with overclamps for the second setup, supports or a subplate need to be placed under the part to raise the part due to end milling of a side. In a fixture plan with overclamps for the last setup, the part overhangs the sine plate to avoid the danger of machining the plate by cutters. The sine plate directly supports the part.

We have selected the most highly rated fixture plan with overhead clamps and a vise for each setup. Because each fixture plan for every setup has no problem with part deflection, the selection was made quickly as soon as the most highly rated fixture plan was displayed. Figures 7-13, 7-14, and 7-15 show the most favorable fixture plans for each setup. While only the fixture plan with a vise is available for setup 1, both plans with clamps and fixture plans with a vise are available for the second and third setups.

A vise installed on the base plate for the first setup can be also used for the second and third setups. If a fixture plan with a vise can be used for all three setups, the time and cost of fixture assembly with a vise is much less comparing to fixture plans with clamps for the second and third setups. Thus, we recommend fixture plans with a vise for all three setups. In fact, for the same sequence of setup plans, tool designers at Pratt & Whitney have also generated fixture plans with a vise for all three setups and have not considered fixture plans with overhead clamps [Barash 89].

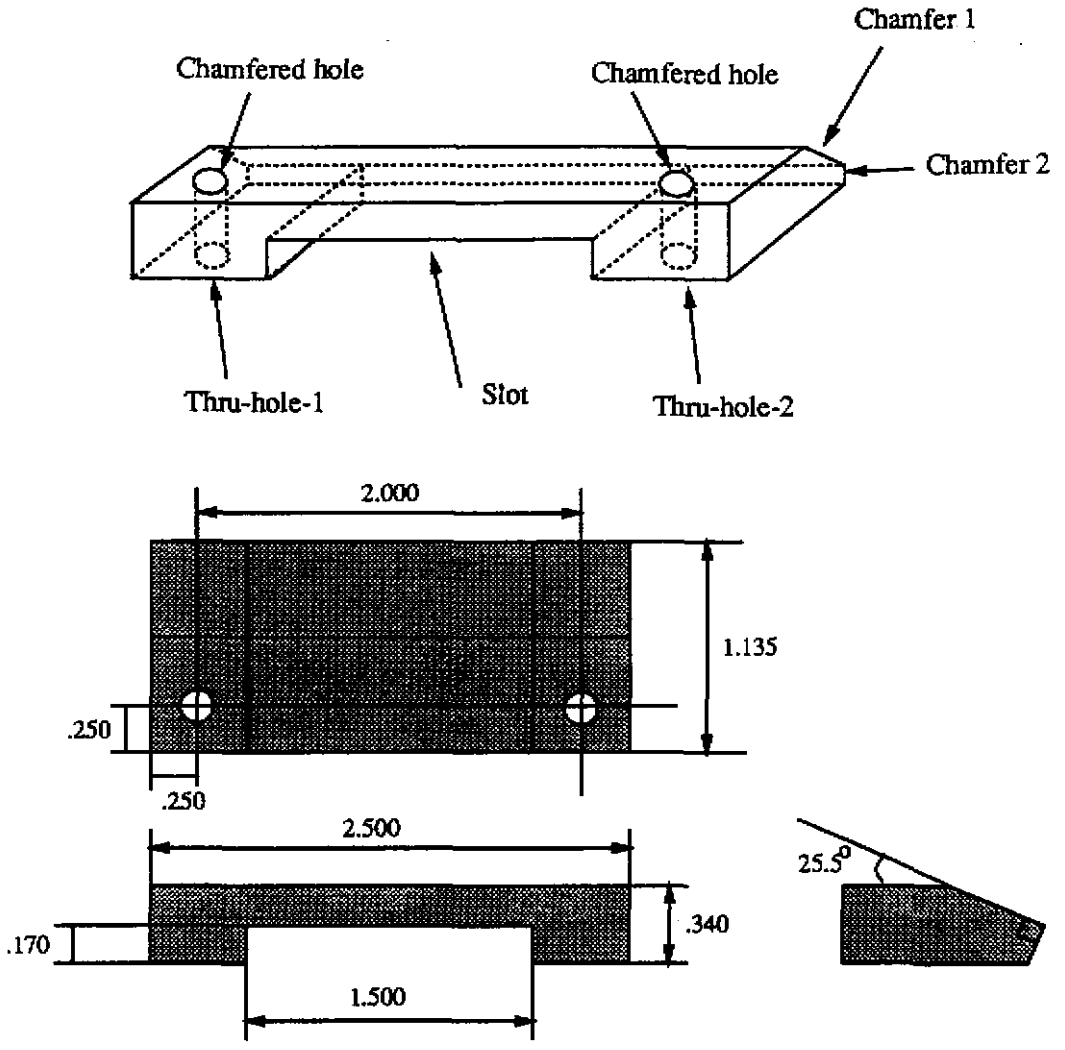


Figure 7-12: Part geometry of a double chamfer part and features

7.6. Example 2: Boomerang Part

Figure 7-16 shows a part geometry of an engine bracket and manufacturing features. There are three through-holes to be installed, and the entire contour of the part needs to be machined.

Because of constraints from features, it turns out that at least 3 setups are required to make the part. In the first setup, the part's top surface needs to be face milled to size. In the second setup, three through-holes and linear contours on the sides are to be made. In the third setup, circular contours are to be made.

For the first setup, the system generated a fixture plan with a vise. For the second and third setups, the system generated multiple fixture plan with overhead clamps. Figure 7-17 shows the most favorable fixture plans selected for each setup. Locators are shown in dotted lines in the fixture plans for the second and third setups because they need to be removed from the base plate to avoid interference with the cutter paths after locating and clamping the part.

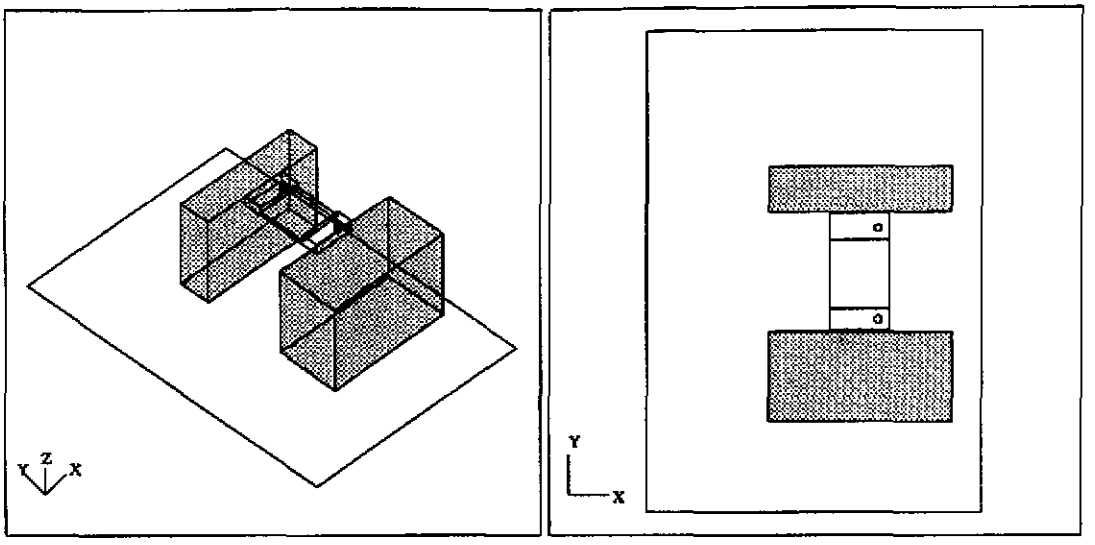


Figure 7-13: A fixture plan for setup 1 of the double chamfer part

7.6.1. Demonstration by Machining

In order to demonstrate the practicality of the system in the industry, a test part similar to the boomerang part is designed (see Figure 7-18). The test part has no holes, and its dimension is about two times larger than the boomerang part. We have generated a sequence of 3 setup plans manually.

For each setup, the machinist has generated cutting plans for features and written by considering the location of the part zero in each setup in the machine coordinate. The system has generated fixture plans and We have selected the most favorable fixture plan for each setup. Figure 7-19 shows the simulated part/fixture assembly and the actual implementation for each setup. (Note: Figure will be completed later.) We have used a subplate to support the part because a thin part requires a careful support to avoid part deflection and vibration. Locators are shown in dotted lines in the fixture plans for the second and third setups because they need to be removed from the base plate to avoid interference with cutter paths after locating and clamping the part.

7.7. Results

Both the speed and quality of fixture planning are critical since they directly affect the time and quality of setup plans. The existing CAD-based fixture planner requires a human expert to take a significant amount of time in selecting necessary components and determining their locations. Also, the quality of fixture plans entirely depends on a human expert's experience and intuition.

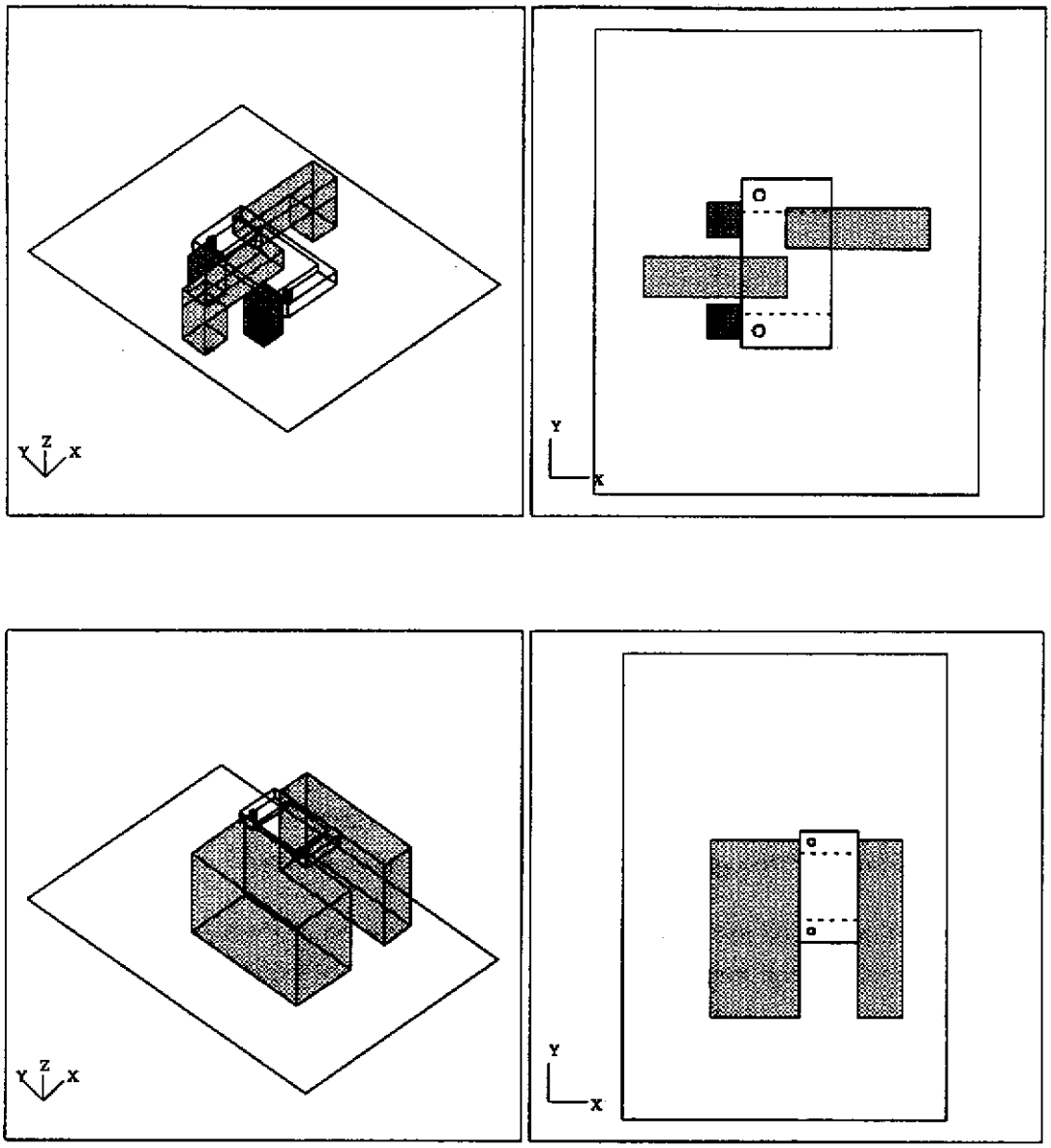


Figure 7-14: Fixture plans for setup 2 of the double chamfer part

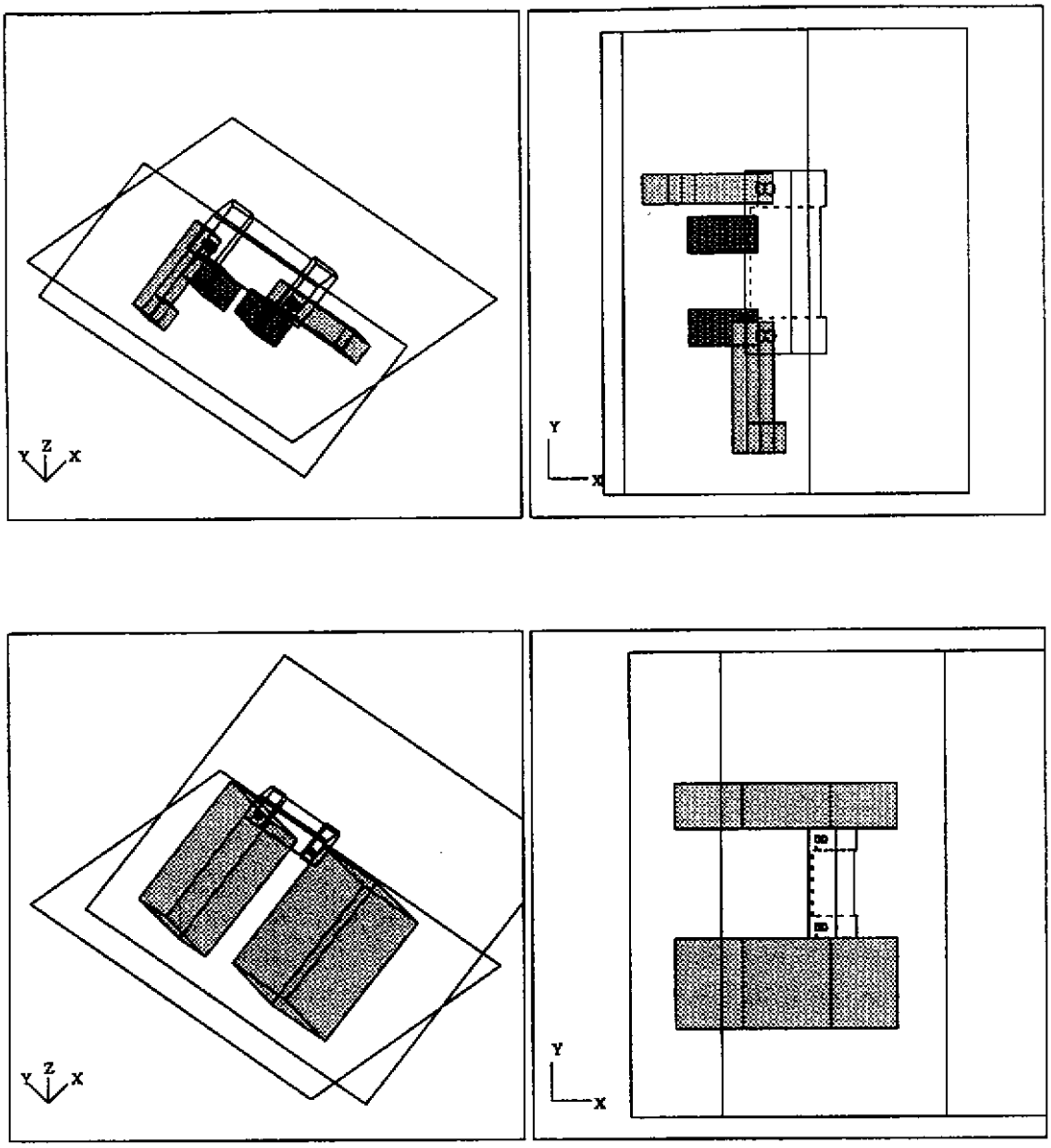


Figure 7-15: Fixture plans for setup 3 of the double chamfer part

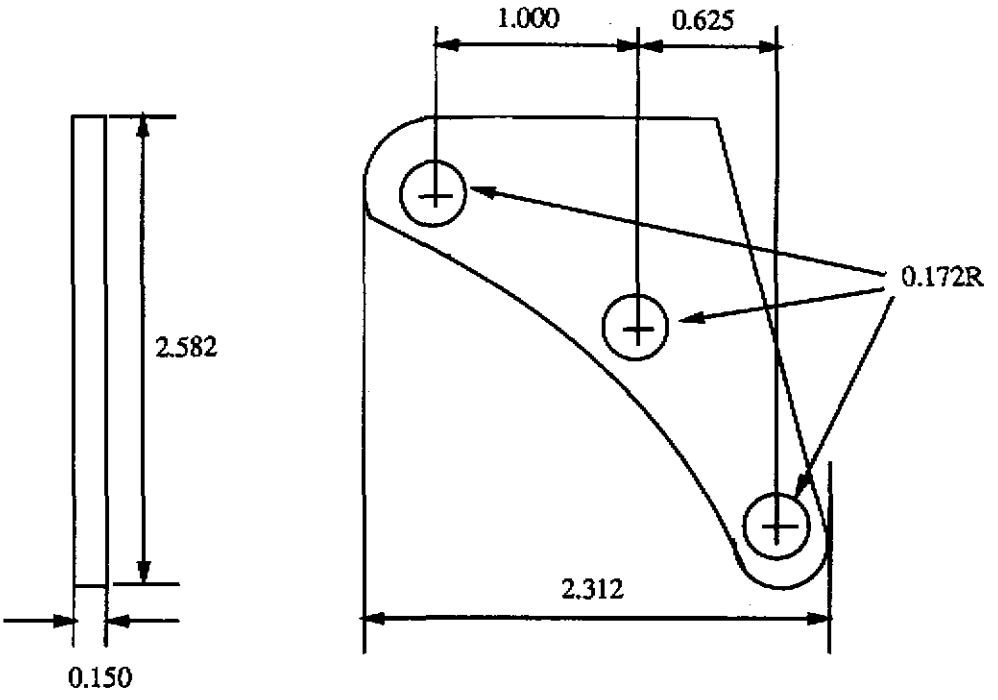


Figure 7-16: Part geometry of the boomerang part and features

7.7.1. Speed of Fixture Planning

Speed of fixture assembly in each setup is often a critical factor that affects the cost of the product with a large batch size. While the cost-effectiveness of setup plans may not be critical for a small batch size production, it becomes more important when the batch size increases, since the overall cost of the production increases with the time spent at various processes. Because both fixture planning and assembly typically take long time, the generation of cost-effective fixture plans for each setup is crucial in generating a cost-effective setup sequence during setup planning.

While the algorithm for fixture planning with a vise finds at most several candidate plans, the algorithm for fixture planning with overhead clamps may find a large number of candidate fixture plans. The number of candidate plans increases with the number of clampable locations. Thus, the speed in generating fixture plans with overhead clamps heavily depends on the size of spacing used to discretize the edges of clampable part faces. For example, if the cutting operation is to drill a hole in the middle of a large rectangular block, the algorithm will identify many valid clamp locations on the part. Therefore, the number of candidate fixture plans could be very large if the spacing is small.

When a part is under either familiar or simple cutting operations, a tool designer may generate a fixture plan more quickly than the existing CAD-based fixture planner or the proposed system can generate one. For example, when squaring raw stock to rectangular block, an experienced tool designer can quickly hold the part with a vise without the aid of any fixture planner.

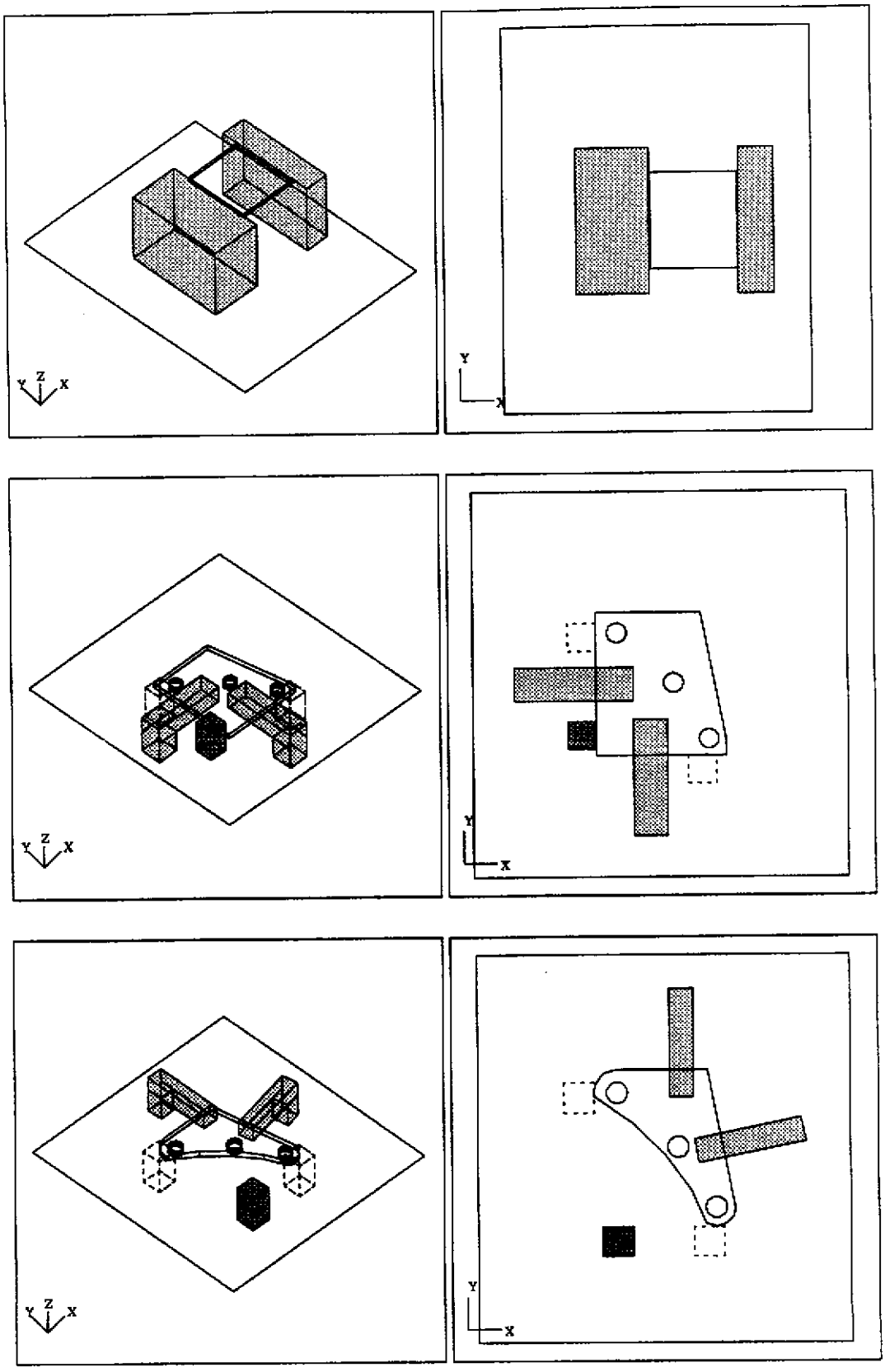


Figure 7-17: Fixture plans for 3 setups of the boomerang part

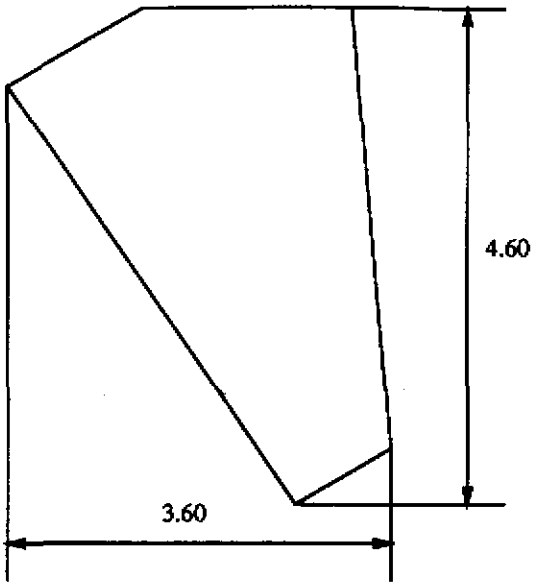


Figure 7-18: Part geometry of a test part

The speed of generating the fixture plan of the system can be compared with the speed of generating the fixture planning when a human expert uses a CAD-based fixture planner. The speed of generating a fixture plan heavily relies on the user's familiarity with the fixture planner and the complexity of a candidate setup plan. Because the proposed system automatically selects necessary components from the fixture data base and determines their locations, the time to generate fixture plans can be significantly reduced.

The system typically generates fixture plans with overhead clamps or a vise within a few CPU seconds on Sun 3/260 when a search space is small. Even when the search space is large, it usually takes less than 30 seconds. The use of more powerful computers can reduce the generating time further.

The time spent by the human viewing and selecting the favorable plan is often longer than the time spent generating fixture plans by the system. The time spent by a human expert in selecting may vary depending on the complexity of the part and cutting plans. When there is no part deflection problem in a highly rated fixture plan by the system, the plan selection can be done quickly. However, if part deflection exists in a highly rated fixture plan, it would take a longer time for further searches. In the system, part deflection checking is done by a human expert. If part deflection checking is automatically performed with the aid of FEM, it would take a significant amount of time for analysis and evaluation unless a fast deflection measuring scheme is used.

Te IMW, with the proposed system implemented in the Holding Expert, took five minutes to dynamically generate process plans for the production of the engine brackets. The same activities would typically require 17 to 40 hours of manual effort prior to actual machining [Barash 89].

Chapter 8
Discussion

8.1. Summary

This thesis describes a system that automatically generates cost effective fixture plans with a modular fixturing system. Algorithms have been developed for fixture planning using overhead clamps and a vise as active components. The system considers actual fixture geometries and their physical limitations such as clamping forces and clampable heights to generate practical fixture plans. Each algorithm for fixture planning with overhead clamps and vises is composed of geometric reasoning, fixturing principles, and analytic tools to automatically generate and determine the candidate locations for fixture components.

Interference checking algorithms have been used along with simple schemes to speed up the computation. Kinematic analysis based on the extended screw theory has been used to prevent part rotation due to clamps during the fixture assembly process. For practicality, a 2D force model is used to estimate necessary clamping forces. Constraints represented as equations from statics and inequality equations are used to model friction with Coloumb's law. A linear programming method, the simplex method, is used to solve the linear optimization problem.

In order to speed up interference checking between the fixture and part/cutter paths/fixture, the geometries of the fixture components and the swept volume of cutter paths are simplified to polyhedra such as rectangular blocks with a small number of faces. Data bases for passive fixture components are composed of parameters describing the dimension of the polyhedra that define the components. Data bases for clamps are composed of parameters describing the dimension of the polyhedra and the physical limitations such as maximum clamping force, minimum and maximum clampable height, and adjustable length of the clamp bar, etc.

In each algorithm, valid clamping plans are generated before the locating/supporting plan because clamping imposes major constraints on a fixture plan.

8.1.1. Fixture Planning with Overhead Clamps

Candidate clamp locations are generated by discretizing the boundaries of the clampable part surfaces with a spacing. In order to speed up the process, fixture constraints that can be checked precisely are applied first to quickly reduce the search space for candidate fixture locations. At each candidate clamp location, interference between the clamp at the location and cutter paths/part is checked, and part rotation due to clamping is checked. These candidate locations are used to exhaustively generate candidate fixture plans starting with the minimum number of clamps. For each candidate plan, interference among the clamps is checked, and the clamping force is estimated. For each valid clamping plan, a locating and supporting plan is generated considering the fixture library and then by checking the interference between the plan and the clamps and the cutter paths. Some valid clamping plans become invalid when a locating plan cannot be generated.

8.1.2. Fixture Planning with a Vise

2D geometric reasoning is developed to identify every possible collision-free contact area for jaw placement considering interference with the cutter paths and part stability during clamping by a movable jaw. The concepts of "contact planes" and "common contact area" are introduced to identify various ways to hold the part in order to consider the physical limitation of a vise and part geometry.

For each collision-free contact area, the jaw locations are determined such that the jaw and the part may have the maximum contact area. The height and location of the parallel bars are determined in consideration of the fixture library and cutter paths.

8.1.3. Results

Several setup examples have been tested to demonstrate the system's capability. The system searches for both fixture plans with clamps and fixture plans with a vise that satisfy various fixturing constraints. Often, the system generates multiple fixture plans with both clamps and a vise. Typically, a fixture plan with less clamping force is more favored by a human expert because there is less chance of part deflection. A human expert (either a tool designer or a process planner) selects a favorable fixture plan, displays its simulated part/fixture assembly on a graphics screen, and inspects for part deflection and any other problems.

In most cases, we were able to quickly view and inspect the simulated part/fixture assembly of a selected fixture plan on a graphics screen for likely part deflection and other problems. For setups tested in Chapter 7, the system generated fixture plans within 2 to 5 CPU seconds.

Fixture plans were successfully generated for each setup in order to make two small test parts with a pre-determined setup sequence. For a test part similar to the boomerang part's shape, the fixture plans were generated by the system for each pre-determined setup sequence, and the part was successfully machined from raw stock.

8.2. Discussion

The system is able to deal with any part shapes because the geometric reasoning used to search the location of the fixture components is formulated independent of the part shape. The system can be used either for generating fixture plans for a given setup as a computer aided fixture planner (CAFP) or included into a computer-aided process planning (CAPP) system to generate fixture plans for each setup.

8.2.1. Algorithm for Fixture Planning with Overhead Clamps

The algorithm is applicable to various modular fixturing systems if their fixture components can be simplified into the same polyhedra descriptions used in the algorithm. Parametric representations of the fixture components allow a user to quickly construct data bases when a new modular fixturing system is introduced or to modify the existing data bases with ease when there are changes in the fixture library. The algorithms' geometric reasoning is independent of the shape or size of the part geometry because the reasoning uses a boundary representation of the part geometry. As a result, the algorithm can be applied to any part shapes or sizes.

The algorithm for generating a fixture plan with overhead clamps assumes that a modular fixturing system is flexible enough to install fixture components at the specified locations and orientations. Risers and a base plate's T slots (or pin holes) can provide flexibility in positioning and orienting the clamp on the part. If the modular fixturing system does not provide this flexibility, the algorithm should be modified to generate candidate clamp locations considering the physical limitation on location and orientation of a clamp on the base plate.

Modular fixturing systems are composed of various fixture components which provide a number of fixture solutions to hold a variety of part shapes and sizes. The proposed system has generated fixture plans with overhead clamps or a vise for parts that can be located and supported according to the 3-2-1 rule with pins or block type locators and supports. In practice, a V-block is used to locate and support the cylinder type parts, and two locating pins can completely locate the part when they are inserted in the holes of the part and the base plate. Since these type of locating plans can be achieved independent of the clamping plan, the current algorithm can be used with minor modifications.

8.2.2. Algorithm for Fixture Planning with a Vise

The algorithm for fixture planning with a vise can be applicable to grasp planning with a parallel jaw gripper with little modification because both the vise and the gripper impose similar constraints in planning.

We have not considered fixture plans with side clamps. A side clamp applies its clamping force parallel to the base plate against the part's reference sides. A movable vise jaw can be considered as a special case for side clamps. Because side clamps do not have to apply their force perpendicular to the part's reference sides, they can be used to hold non-rectangular parts. Although a vise is usually preferred to side clamps

for holding rectangular parts due to its economy, side clamps may provide more cost effective fixture plans than the vise.

8.2.3. Extension to Other Machines and Processes

The proposed system considers fixture planning for parts that require milling operations. Both algorithms can be applied to a 5 axis/horizontal milling machine with little or no modification. The structure of the algorithm, geometric reasoning, and analytical tools can be applied to an automated assembly problem or grasping problem since their constraints in the assembly plan or grasp plan are similar.

8.2.4. Part Deflection

The most difficult problem in fixture planning is to detect and prevent excessive part deflection in a fixture plan. This system does not generate fixture plans that consider this part deflection problem. Thus, a human is required to inspect part deflection in a fixture plan. While a human experienced in fixturing may be able to quickly make a proper decision on part deflection, it will be a challenging task for an less experienced human expert. Less experienced human experts may spend a long time evaluating and end up generating a plan that is too conservative. For a more accurate measurement of part deflection, the finite element method (FEM) may be employed [Lee 86] [Menassa 88].

8.2.5. Assembly Issues

A variety of commercially available modular fixturing systems exist. In all of these modular fixturing systems, the base plate typically has T slots or pin holes to install fixture components and may limit the location and orientation of a fixture component. The current system assumes that the modular fixturing system is flexible enough to implement fixture plans on the base plate as specified by the algorithms.

While the assembly of a fixture plan with a vise according to the plan is hardly limited by the base plate, a modular fixturing system with less flexibility may not allow fixture components for a fixture plan with overhead clamps to be placed according to the locations and the orientation specified by the algorithm. For the less flexible modular fixturing system, the algorithm should consider the limitation of the base plate and fixture components in order to generate valid candidate locations that can be implemented according to the plan.

The system may not generate fixture plans for a candidate setup for a variety of reasons. Generally, the reason is that part geometry or cutter paths not allow the places for fixture components necessary for a complete fixture plan. Also, a fixture plan cannot be generated when the necessary clamping force for a movable vise jaw or overhead clamps (with the use of maximum number in the fixture library) exceeds the maximum clamping force of the vise or the clamp. When the system cannot generate a fixture plan with either a vise or overhead clamps, the setup should be divided into multiple setups to allow room for fixture components or the magnitude of the cutting force needs to be reduced by adjusting the cutting parameters.

8.2.6. Generating the Most Cost-efficient Setup Sequence

The speed during the fixture assembly and the cutting operation affects the cost of the product. Therefor the need to reduce cycle time becomes important if the batch size is large. Because the fixture assembly typically takes a long time, the generation of inexpensive fixture plans for each setup is crucial in generating an inexpensive setup sequence during setup planning.

Typical setup planning for a machined part requires multiple setups in order to create the part from raw stock. A candidate setup often can have fixture plans both with overhead clamps and a vise. In a typical setup sequence, usually fixture plans with a vise are available in earlier setups while fixture plans with overhead clamps are available in later setups. The conventional fixturing process with or without a CAD based fixture planner (CAFP) to generate a fixture plan typically takes a long time. Also, a less experienced human could generate a fixture plan which is too conservative requiring many clamps with a large clamping force. Because this may require a significant amount of time with conventional fixture planning, a human expert typically cannot afford to search for the optimal setup sequence or is discouraged from doing so. The proposed system can enable the human expert to generate an optimal setup sequence quickly.

In order to generate the most time efficient series of fixture plans for the given sequence, fixture plans that require little time for assembly are usually preferred. Every possible series of fixture plans needs to be generated, and the fixture assembly time should be estimated for each candidate series. The total fixture assembly time may vary significantly depending on the sequence of fixture plans. Both a vise and a clamp take longer time to assembly on a base plate. However, a vise installed on a base plate for a setup can often be used for subsequent setups, while a clamp needs to be disassembled and reassembled in most setups. A human expert can select the most favorable series of fixture plans considering the overall fixture assembly time and other criteria such as cutting cost and part accuracy.

In Chapter 7, the system has generated fixture plans for a candidate setup sequence with 3 setups for the double chamfer part. While only fixture plans with a vise are possible for the first setup, either overhead clamps or a vise can be used for the second and third setups. A possible series of fixture plans can be generated as follows:

Series	setup 1	setup 2	setup 3
A	vise	vise	vise
B	vise	vise	clamps
C	vise	clamps	vise
D	vise	clamps	clamps

Because the same vise can be used for the entire setup with the single installation, series A will be the least expensive series of fixture plans.

Often, more than one candidate setup sequences can be generated during the setup planning. A setup sequence may have a different number of setups from another sequence. After generating the possible candidate fixture series and performing the cost analysis, a human expert can identify the most inexpensive

series of fixture plans for each candidate setup sequence. By comparing the time for total fixturing and cutting operations for every candidate setup sequence, a human expert can select the most cost-effective setup sequence.

Chapter 9

Conclusion

The contributions of the thesis can be summarized as follows:

1. Development of an algorithm for automated fixture planning with overhead clamps
   - A finite search space for locations for clamps and locators is generated by discretizing relevant part surfaces in consideration of practical constraints.
   - Candidate clamping, locating, and supporting locations are generated by considering fixturing principles, fixture constraints, and fixture library.
   - Fixture plans are generated using the minimum number of clamps with minimum clamping force in order to minimize assembly costs and avoid part deflection problems.
2. Development of an algorithm for automated fixture planning with a vise
   - The conventional fixture planning systems are used only for fixture plans with overhead clamps. Fixture planning with a vise is done without the aid of computer. With the algorithm proposed in this thesis, an optimal fixture plan with a vise can be quickly identified.
   - 2D geometric reasoning is used to identify multiple candidate collision-free contact areas for the jaw and determine their locations. Each candidate contact area is non-redundant in that the contact area is not a subset of other contact areas. Thus, each fixture plan will require different amounts of clamping force.
   - The minimum clamping force is estimated for each plan to minimize the danger of part deflection.
3. Development of 2D force analysis to estimate clamping force for a candidate fixture plan with either clamps or a vise
   - The conventional approach estimates the clamping force conservatively by considering the cutting forces applied to the part. As a result, the large number of clamps may be required and thus large clamping force is applied to the part. This may cause the part to deflect at the clamping location or the fixture assembly time and cost may be increased. In order to generate the optimal fixture plans with the minimum number of clamps and the minimum clamping force, the proposed algorithm considers cutting force and direction when estimating the clamping force.
4. Generation of fixture plans with a minimum number of clamps and minimum clamping force
   - For fixture plans either with clamps or a vise, the algorithms typically generate multiple plans. Fixture plans are rated by the magnitude of the required clamping force. A human expert can select the most favorable fixture plan which is usually the plan with the least clamping force. As a result, part deflection due to clamping force can be minimized.
5. Generation of practical fixture plans
   - Previous research on automated fixture planning with a generative approach has generated candidate locations without considering fixture components' geometry. Thus, a tool designer is required to select appropriate fixture components and check if

the fixture plan violates any fixture requirements. This process may require many iterations that would take a long time. This system quickly generates fixture plans in which fixture components are automatically selected by considering the fixture components' geometry/limitation and fixture constraints. Since a human expert's intervention is reduced to checking for possible part deflection (and to completing support for fixture plans with clamps when the part is raised from the base plate), the time for fixture planning can be greatly reduced.

6. Complete interference checking between the fixture components and the part/fixture components/cutter paths

7. Application of screw theory to check part rotation due to the clamping location

8. Extendibility of algorithms to various modular fixture systems

   - This system only considers parts that can be located by the 3-2-1 rule with locators or a touch probe. In fixture planning with overhead clamps, other locating methods can also be considered in the algorithm with little modification.

   - Fixture components' geometry and limitations are parameterized in a data base. Thus, the algorithm developed for fixture plans with overhead clamps can handle various types of overhead clamps as far as they can be modeled as L-shape polyhedra. If the clamp is difficult to model as a L-shape polyhedron due to its complex geometry, a different polyhedron with a new set of parameters should be used.

Chapter 10

Future Work

We suggest the following as areas for the future research in order to further automate fixture planning using modular fixtures for various part shapes.

- The algorithm for automated fixture planning with overhead clamps is limited to parts that can be located by the 3-2-1 rule. Other locating methods also should be considered.
- More precise force models with a well estimated cutting force and direction should be developed since they are critical in the estimation of the clamping force and the evaluation of part deflection.
- Although FEM can measure the part deflection in a fixture plan, it is rarely used in practice since it requires a good analytical model and is computationally expensive. Thus, it is necessary to develop a technique to quickly measure part deflection with a simplified force model.
- Even if part deflection can be accurately measured, it is a very challenging task for a human expert to decide if the deflection can be tolerated. In order to automate fixture planning further, it is desirable to develop a scheme that can automatically determine the severity of part deflection in a fixture plan. A comparison between the part geometry with and without cutting/clamping forces along with AI techniques may be used to detect untolerable part deflection.
- The algorithm for fixture plans with overhead clamps may generate numerous plans depending on the inputs in a given setup. Even when part deflection checking is automated, it is often necessary for a human expert to select a favorable fixture plan while checking any other problem during actual assembly. Since this selection process can often take a long time, it is desirable to develop a scheme to aid the human in plan selection.
- Side clamps should be added to the system in such a way that the tradeoffs between overhead clamping and side clamping are understood and taken advantage of.

Appendix A
Screw Theory

In this section, we review screw theory and present a mathematical technique using linear programming in order to solve a set of simultaneous linear inequality equations.

A.1. Review

Screw theory was first introduced by Ball [Ball 00] and the concept was extended by Ohwovoriole [Ohwovoriole 80] to analyze the motion of an object during assembly process. The review given in this appendix give a summary of the extended screw theory described in Ohwovoriole's PhD thesis [Ohwovoriole 80]. Most notations are borrowed from Ahmad and Feddema 's paper [Ahmad 87]. Screw theory is based on screw systems in which generalized forces and displacements are represented as wrenchs and twists, respectively. A screw, s, is defined by a straight line in space with its axis and pitch. s can be described as the following.

$$\mathbf{s}=(s_1,s_2,s_3;s_4,s_5,s_6)$$

A twist is a screw with a linear velocity along it and an angular velocity about it. A twist, T, may be represented as

$$\mathbf{T}=(\omega;\mathbf{r}\times\omega+\mathbf{v}) \quad \text{or}$$
$$\mathbf{T}=(\mathbf{t};\mathbf{t}_o)=(t_1,t_2,t_3;t_4,t_5,t_6)$$

where ω is the angular velocity about the axis and $\mathbf{v}$ is the linear velocity along the axis. $\mathbf{r}$ is a position vector to an arbitrary point on the twist axis. $\mathbf{t}=(t_1,t_2,t_3)$ and $\mathbf{t}_o=(t_4,t_5,t_6)$.

A wrench is a screw with a linear force acting along it and a moment acting about it. A wrench, W, may be represented as

$$\mathbf{W}=(\mathbf{f};\mathbf{r}\times\mathbf{f}+\mathbf{m}) \quad \text{or}$$
$$\mathbf{W}=(\mathbf{w};\mathbf{w}_o)=(w_1,w_2,w_3;w_4,w_5,w_6)$$

where $\mathbf{f}$ is the linear force vector, $\mathbf{m}$ is the moment vector, and $\mathbf{r}$ is a position vector to an arbitrary point on the wrench axis. With a pure wrench that applies only force, $\mathbf{m}$ becomes zero. $\mathbf{w}=(w_1,w_2,w_3)$ and $\mathbf{w}_o=(w_4,w_5,w_6)$.

The virtual work $\mathbf{dW}$ of a wrench $\mathbf{w}$ acting on a twist $\mathbf{t}$ is defined as

$$\mathbf{dW}=\mathbf{W}\cdot\mathbf{T}=\mathbf{w}\cdot\mathbf{t}_o+\mathbf{w}_o\cdot\mathbf{t}$$

If $\mathbf{dW} = 0$, two screws are known to be reciprocal. If $\mathbf{dW} > 0$, two screws are known to be repelling. If $\mathbf{dW} < 0$, two screws are known to be contrary.

Ohwovoriole [Ohwovoriole 80] applied screw theory to either prove or identify any unrestrained motion of an object when a set of frictionless point contacts are placed around an object. A frictionless point contact, either passive or active, can only have a force normal to its contact surface and can be described by a wrench.

According to screw theory by Ohwovoriole, the motion of an object is completely restrained when there exist no twists either reciprocal or repelling to every wrench applied to the object. In other words, if every possible twist is contrary to at least one wrench, the motion of an object is restrained.

Each contact is described by a wrench and A is a m by n matrix described as $A = [w_1, \ldots, w_m]^T$, where w_i is a wrench at ith contact, m is the number of wrenches. A twist is described by $T = [t_1, \ldots, t_n]^T$ where n is 6 in 3D and 3 in 2D. Then, the necessary and sufficient condition for a complete restraint of an object's motion is that for $A\,T \geq 0$, there should exist only the trivial solution for T since either repelling or reciprocal twists to any wrench should not exist.

A.2. Solving a set of linear inequality equations

It is known that the homogeneous system $A\,x = 0$ of m equations in n variables has a solution space of dimension n - r, where r is the rank of A where A is a m by n coefficient matrix and $x = [x_1, \ldots, x_n]^T$ [Roberts 82]. In this system, always $n \geq r$.

- if n = r, then the solution space has dimension 0; the trivial solution is the only solution (To have $\square$ = r, m should be greater than or equal to n).
- if n > r, the solution space has dimension n - r > or 0; the nontrivial solution exists (Note that if n > m, always n > r).

Thus, for $A\,T = 0$ to have only the trivial solution, the rank of a wrench matrix should be 6 in 3D because n = 6. In other words, there should be 6 independent wrenches in a wrench matrix. To also have only the trivial solution for $A\,T \geq 0$, at least 7 wrenches (or 7 frictionless contacts) are required to restrain an object completely in space, and 6 of them should be independent wrenches. In 2D, n = 3 and at least 4 wrenches are required and 3 of them should be independent wrenches.

Ohwovoriole [Ohwovoriole 80] solved for T from simultaneous linear inequality equations by using the theory of polyhedral convex cones [Goldman 56]. While this method can find a general expression of a solution, it is computationally intensive and difficult to program. Since our intention is to check whether there exist only trivial (zero) solutions, a faster and more easily programmable method is preferred. Another method to check the existence of the solution for a set of linear inequality equations is to use a linear programming (LP) method such as the simplex method. A standard format for the simplex method is given in the following [Taha 82]:

Maximize or minimize $z = \sum_{j=1}^{n} c_j x_j$

Subject to:

$$\sum_{j=1}^{n} a_{1j} x_j \le b_1$$
$$\sum_{j=1}^{n} a_{2j} x_j \le b_2$$
$$\cdots$$
$$\sum_{j=1}^{n} a_{mj} x_j \le b_m$$
$$x_1, \ldots x_n \ge 0, \quad b_1, \ldots, b_m \ge 0$$

where m is the number of constraint equations, n is the number of unknown variables, and i = 1, . . . , m. x_j is a variable and a_{ij}, b_i, and c_j are constants.

The problem to solve a set of simultaneous inequality equations is converted into an optimization problem. In this, the objective function is each component of T, $\mathbf{T} = (t_1, t_2, t_3 ; t_4, t_5, t_6)$ in 3D while it is subject to constraints $\mathbf{A\,T} \ge 0$ and each component of **T** is unrestricted. According to the standard LP format, the problem can be formulated as follows:

For $j = 1, \ldots, m$
Maximize and Minimize $z = t_j$
Subject to :

$$-\mathbf{A}_1 \mathbf{T} \le 0.$$
$$-\mathbf{A}_2 \mathbf{T} \le 0.$$
$$\cdots$$
$$-\mathbf{A}_m \mathbf{T} \le 0.$$
$$t_1, \ldots t_n \textit{ unrestricted.}$$

where n is the number of components in screw coordinate (n is 6 in 3D and 2 in 2D). m is the total number of wrenches. Since t_j is an unrestricted variable, it needs to be expressed in terms of two nonnegative variables by using the substitution $t_j = p_j - q_j$ for j = 1, . . . , n where $p_j, q_j \ge 0$.

To restrain an object's motion completely, every objective function $z = t_j$ should have only the trivial solution. If any objective function has a non-trivial solution, there exist a twist reciprocal or repelling to every wrench. By investigating the existence of a non-trivial solution for each t_j, the existence of every possible twist of the object can be identified. For example, if the maximization or minimization of t_3 has an unbounded solution, the object can have positive (counter clockwise) rotation or negative (clockwise) rotation about the Z axis. If the maximization or minimization of t_4 has an unbounded solution, the object can have positive translation or negative translation along the X axis. The simplex method has been implemented using routines in Numerical recipes in C [Press 88].

References

[Ahmad 87] Ahmad S., Feddema, J. T.
Static Grip Selection for Robt-Based Automated Assembly Systems .
Robotic Systems 4(6):687-717, Dec, 1987.

[Asada 85] Asada, H. and By, A. B.
Kinematic Analysis of Workpart Fixturing for Flexible Assembly with Automatically Reconfigurable Fixtures.
IEEE Journal of Robotics and Automation 1(2):86-93, 1985.

[Ball 00] Ball, R. S.
A Treatise on the Theory of Screws.
Cambridge University Press, 1900.

[Barash 89] Barash, D. et al.
Intelligent Machining Workstation: IMW Program Abstract.
Technical Report, Cincinnati Milacron, Cincinnati, OH., May, 1989.

[Barber 86] Barber, J. et al.
Automatic Two-Fingered Grip Selection.
In *IEEE Int. Conf. on Robotics and Automation*, pages . April, 1986.

[Barkocy 84] Barkocy, B. E. and Zdelick, W. J.
A Knowledge-Based System for Machining Operation Planning.
In *Proceedings of AUTOFACT 6*, pages 77-88. 1984.

[Bourne 88] Bourne, D. A. et al.
Interim Report for Period April, 1988 - June 1988, U. S. Air Force Technical Report (AFWAL-TR-88-4152).
Technical Report, Wright Patterson Air Force Base, Dayton, OH., June, 1988.

[Chang 83] Chang, T. C. and Wysk, R. A.
CAD/Generative Process Planning with TIPPS .
SME Journal of Manufacturing Systems 2(2):127-135, 1983.

[Chou 88] Chou, Y. C. .
Automatic Design of Fixtures for Machining Processes.
PhD thesis, Purdue University, 1988.

[Crandall 78] Crandall S. et al.
An Introduction to the Mechanics of Solids.
McGraw-Hill Book Company, 1978.

[Descotte 81] Descotte, Y. and Latombe, J.
GARI: A Problem Solver That Plans How To Machine Mechanical Parts.
In *Proc. 7th International Joint Conf. on Artificial Intelligence*, pages 766-772. Aug, 1981.

[Englert 87] Englert, P. J.
Principles for Part Setup and Workholding in Automated Manufacturing.
PhD thesis, Carnegie Mellon University, Department of Mechanical Engineering, 1987.

[Ferreria 85] Ferreria, P. M., Kochar, B., Liu, C. R., and Chandra, V.
AIFIX: An Expert System Approach to Fixture Design.
In *ASME Symposium on Computer Aided/Intelligent Process Planning*, pages 73-82. 1985.

[Goldman 56] Goldman, A. and Tucker A.
Polyhedral Convex Cones.
Linear Inequalities and Related Systems, Annals of Math. Studies 38:19-39, 1956.

[Gouldson 79] Gouldson, C. J.
Principles and Concepts of Fixturing for NC Machining Centers.
In *SME's Jigs and Fixtures Clinic*, pages 331-349. March, 1979.

[Grippo 87] Grippo, P., Gandhi, M., and Thompson, B.
The Computer Aided Design of Modular Fixturing Systems.
The International Journal of Manufacturing Technology 2(2):75-88, 1987.

[Gursoz 91] Gursoz, E.
Reference Manual for the NOODLES Library.
Engineering Design Research Center, Carnegie Mellon University.
May, 1991

[Handbook 88] .
Tool and Manufacturing Engineering Handbook.
Society of Manufacturing Engineering, 1988.

[Hayes 87] Hayes, C. C.
Planning in the Machining Domain: Using Goal Interaction to Guide Search.
Master's thesis, Mellon College of Science, Carnegie Mellon University, 1987.

[Hayes 91] Hayes, C. C.
Machining Planning: A Model of an Expert Level Planning Domain.
PhD thesis, Carnegie Mellon University, Robotics Institute, 1991.

[Hoffman 87] Hoffman, E. G.
Modular Fixturing.
Manufacturing Technology Press, 1987.

[Ingrand 84] Ingrand, F. and Latombe, J.
Functional Reasoning for Automatic Fixture Design.
In *Proceedings of CAM-I's 13th Annual Meeting and Technical Conference*, pages 53-65. 1984.

[Kerr 84] Kerr, J. R.
An Analysis of Multi-fingered hands.
PhD thesis, Stanford University, Dept. of Mechanical Engineering , 1984.

[Kim 85] Kim, K. H.
Dynamic Direct Subspace Appraoch for Robot Task Planning in Three Dimensions.
Master's thesis, Brigham Young University, Dept. of Mechanical Engineering, 1985.

[Laugier 81] Laugier, C.
A Program for Automatic Grasping of Objects with a Robot Arm.
In *Proc. 11th Int. Symp. on Industrial Robots*, pages 287-294. Oct., 1981.

[Lee 86] Lee, J. D. and Haynes, L. S.
Finite Element Analysis of Flexible Fixturing Systems.
In *Proc. ASME Japan-USA Symposium on Flexible Automation*, pages 579-584. 1986.

[Mani 88] Mani, M. and Wilson W. R. D.
Automated Design of Workholding Fixtures using Kinematic constraint synthesis.
In *The Proceeding of the 16th North American Manufacturing Research Conference of SME.* Urbana-Champaign, IL, May, 1988.

[Markus 84] Markus, A., Markuz, A., Farkas, J., and Filemon, J.
Fixture Design Using PROLOG: An Expert System.
Robotics & Computer Integrated Manufacturing 1(2):167-172, 1984.

[Mashburn 87] Mashburn, T.
Polygonal Soild Modeling Package.
Master's thesis, Purdue University, Dept. of Mechanical Engineering, 1987.

[Menassa 88] Menassa, R. J. and Devries, W. R.
Optimization Methods Applied to Selecting Support Points in Fixture Design.
In *Proc. ASME Japan-USA Symposium on Flexible Automation*, pages 475-482. 1988.

[Miller 85] Miller, A. S. and Hannam, R. G.
Computer Aided Design Using a Knowledge Base Approach and Its Application to the Design of Jigs and Fixtures.
In *Proc. Instn. Mech. Engrs, Vol. 199 No. B4*, pages 227-234. 1985.

[Nau 87] Nau, D. S.
Hierarchical Abstraction for Process Planning Knowledge Based Expert System in Engineering: Planning and Design .
In *2nd International Conference on Applications of Artificial Intelligence in Engineering Problems*, pages 129-141. Cambridge, MA, Aug, 1987.

[Nee 87] Nee, A. Y. C., Bhattacharyya, N., and Poo, A. N.
Applying AI in Jigs and Fixtures design.
Robotics & Computer Integrated Manufacturing Technology 2(2):75-78, 1987.

[Nnaji 88] Nnaji, B., Alladin, S., and Lyu, P.
A Framework for a Rule-based Expert Fixturing System for Face Milling Planar Surfaces on a CAD System Using Flexible Fixtures.
Manufacturing Systems 7(3):193-207, 1988.

[Ohwovoriole 80] Ohwovoriole, M. S.
An Extension of Screw Theory and its Application to the Automation of Industrial Assemblies.
PhD thesis, Stanford University, 1980.

[Preiss 84] Preiss, K. and Kaplansky, E.
Automated CNC Milling by Artificial Intelligence Methods.
In *AUTOFACT 6 Conference*, pages . October, 1984.

[Press 88] Press, W. H.
Linear Programming and the Simplex Method.
Numerical Recipes in C: the Art of Scientific Computing.
Cambridge University Press, 1988, pages 329-343.

[Reuleaux 76] Reuleaux, F.
The Kinematics of Machinery.
Macmillan and CO., London, 1876, pages 96-114.
Reprinted Dover Publications, Inc. New York, NY, 1963.

[Roberts 82] Roberts, A., W.
Elementary Linear Algebra.
Bejamin/Cummings Publishing Company, 1982.

[Sakurai 90] Sakurai, H.
Automatic Setup Planning and Fixture Design for Machining.
PhD thesis, M.I.T., 1990.

[Smith 89] Smith, G.
Advanced Machines: the Handbook of Cutting Technology.
Springer-Verlag, 1989.

[Su 91] Su, C. and Mukerjee, A.
Automated Machinability Checking for CAD/CAM.
IEEE Transactions on Robotics and Automation 7(5):691-699, Oct, 1991.

[Taha 82] Taha, H.
Operation Research.
Maxmillan Publishing Co., Inc., 1982.

[Wolter 82] Wolter, J. and et al.
Gripping Position for 3D Objects.
In *Proc. 1982 Meeting of the Industrial Applications Soc.*, pages 1309-1314. Oct., 1982.

[Zhu 92] Zhu, Y. and Rong, Y.
A Group technology based Computer-aided Fixture Design System.
In *Computer-aided Engieering and Manufacturing*, pages 199-204. Aug., 1992.