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AUTOMATIC GRIP SELECTION

by

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ABSTRACT

As companies pursue Computer Integrated Manufacturing in an attempt to build flexible manufacturing systems, robots are being used in a variety of material handling operations. Robots in these applications need to have the flexibility to deal with an assortment of parts without being taken out of production or reprogrammed. This thesis describes an approach to automatically determining the way a robot should grasp a part given a CAD description of the part's shape. The approach which is presented enables the robot to be flexible in that parts which have not been grasped previously can be grasped successfully without taking the robot out of production or modifying existing robot programs.

The approach to automatic grip selection consists of three major steps: feature extraction, constraint filtering and selection. Feature extraction is a process for identifying all instances of grip configurations from a CAD description of the part to be grasped. A grip configuration describes how the gripper should contact the part in order to grasp it successfully. Constraint filtering imposes real world conditions upon a set of grip configurations, eliminating those which are not appropiate for the current

state of the environment. Selection is a decision making process in which a grip configuration is selected for use based upon a measure of its applicability to both the part and the environment.

The approach to automatic grip selection presented in this thesis is implemented in the Automatic Grip Selection Module (AGSM). The AGSM is evaluated in two trial cases based upon its performance. The approach is seen to be an effective architecture for grip selection, capable of supporting the implementation of more comprehensive modules for grasping more complex parts.

Chapter 1 - INTRODUCTION TO AUTOMATIC GRIP SELECTION

Robots are being used in modern manufacturing operations to perform a wide variety of material handling tasks such as parts handling, assembly tasks, and the loading and unloading of machine tools. A basic function common to all material handling operations performed by a robot is grasping a part with the robot's gripper.

Robot applications are becoming more complex as robot users integrate robots into manufacturing systems for the purpose of gaining flexibility. A manufacturing system needs to be flexible when several parts are to be produced with the same set of machines. A robot helps realize flexibility because it can be programmed to manipulate several different parts and can therefore adapt its functionality under program control.

An example of a flexible system is a workcell of several machine tools, all of which are loaded and unloaded by a single robot. Each machine is capable of producing several different parts, each of which is shaped differently. The robot must adapt its grasp depending on which part it is loading or unloading.

The adaptation could be implemented in the form of several programs or subroutines executed based upon which part is being grasped and loaded. This approach requires that a robot program be implemented for each new part. Alternatively, the adaptation could be implemented with a parameterized program in which the values of the parameters are determined by which part is being loaded. This approach works well for grasping and loading similarly shaped parts but not so well for dissimilar parts.

A third approach to adapting the performance of the robot grasping and loading parts into a machine is to determine the extent of the adaptation on the basis of the part's shape. This thesis describes an approach for determining the best way to grasp a part, based upon the part's shape and the state of the environment in which the grasping operation is to be performed. This approach is called automatic grip selection.

1.1 - Definition of Automatic Grip Selection

Automatic grip selection is a process for determining how a particular gripper should grasp an object so that a stable grasp is achieved. This process operates on data describing part shape, gripper shape and the position of the part to produce a grip configuration. A grip configuration describes how the gripper should contact the part in order to achieve a stable grasp. A grip configuration is represented as a set of topological entities (shells, faces, edges, holes, etc.) which the gripper contacts.

The inputs to the AGSM are the description of the part shape, the shape and functionality of the gripper, the initial position of the part and the task based final position of the part. The output of the AGSM is a grip configuration which describes how the gripper will contact the part.

1.2 - Rationale for Automatic Grip Selection

There are a number of motivating reasons for automatically selecting grip configurations. Research in robot control systems indicates the need for a task level programming environment. Automatic grip selection is necessary to support task-level programming. The inconvenience and inaccuracy of teach programming grip configurations suggests the application of automatic grip selection to traditionally teach programmed gripping tasks. Coordination between the grip planner and the task can be realized with automatic grip selection and is necessary as robot applications become more complex. These motivating reasons are explained in greater detail in the following sections.

1.2.1 - Task-level programming

In several research institutions, research is currently underway in the development of fourth generation robot controllers. Fourth generation robot controllers

employ a type of programming known as "task-level" programming. Task-level programming attempts to simplify the programming process by requiring that the user specify only goals for the physical relationships among objects, rather than the sequence of actions needed to achieve those goals. A task-level command is meant to be completely robot independent; no positions or paths that depend on the robot geometry or kinematics are specified by the user. An example of a task-level command is "TRANSFER PART from TABLE to VISE".

Given the task-level programming environment, a logical extension of task level programming is automatically selecting a grip configuration. A task level gripper command is "GRASP PART FOR PAINTING". The commander, that is the process which issues the command, will issue the command without regard for how the grasping task will be effected. The commander is not concerned with the shape of the part or the gripper, only that the part be grasped so that it is prepared for painting. Determining how to grasp the part so that it can be painted is the task of the AGSM. The AGSM supports task level programming found in fourth generation robot controllers.

1.2.2 - Teach Programming

Currently, grip configurations are teach programmed by a robot technician. In this method of determining grip configurations, the technician moves the robot arm to the part to be grasped, decides how to grasp the part so that it will stay gripped, and records the robot arm's position. There are several drawbacks to this method of programming grip configurations. The first is that in order to teach program the robot, it must be taken out of production. Teach programming is a time consuming operation and it is desirable to keep capital equipment such as robots and the machines they tend in production as much as possible. Utilizing automatic grip selection to determine grip configurations eliminates the need for teach programming.

In order to teach program grip configurations, a sample part must be available. With strong emphasis being placed upon the flexibility of manufacturing systems to deal with small batch sizes, production of a prototype part becomes undesirable. Indeed some manufacturing research efforts are striving for the flexibility to produce batches of one, as economically as larger batches. Automatic grip selection determines grip configurations based upon a CAD description of the part to be grasped and therefore does not require any prototype in order to determine grip configurations.

1.2.3 - Effective Grip Configurations

An effective grip configuration for a part is achieved when the part is stable while being grasped by the gripper and remains stable while the gripper is moved with the arm,

and when the part is not damaged by the gripping action. The mechanics of gripping involve computing the effects of contact forces upon the part, effects which might be deformation, rotation or translation. Quantities which affect the mechanics of gripping are friction, forces, deformation of the gripper fingers, and the composition of the fingers.

Effective grip configurations for a metal cube are rather obvious - pairs of opposite sides, however, on more complex parts which change from the time they are loaded into a machine tool, the grip configurations are not obvious at all. The shape of the part before and after processing is contained in the CAD/CAM database. The AGSM will use this information to compute a grip configuration which will be an effective grip configuration every time.

Automatic grip selection is a natural application for incorporating an expert system which will aid in the selection of the best grip configuration based upon the mechanics of the gripper and the shape of the part. An expert system permits the expertise of a mechanical expert to be applied to grasping every time that operation is performed by the gripper. The application of expert system techniques to automatic grip selection results in effective grip configurations every time a part is to be grasped, regardless of orientation, task, changing shape or gripper.

1.2.4 - Grip and Task Coordination

A fourth reason for the development of an AGSM is the benefit of coordination between the grasping operation and whatever operation on the part follows. For example, if a robot's task is to grasp a part then present a specific side to a buffing wheel, it is not effective to use a grip configuration which uses that same face. The AGSM must therefore take into consideration the task at hand as well as the subsequent commands which are impacted by part position. In order to perform complex tasks with a robot arm and gripper it is necessary to consider the task context when deciding how to grasp the part.

1.3 - Approach to Automatic Grip Selection

The approach taken to automatic grip selection in this thesis consists of three major stages:

1) feature extraction
2) constraint filtering
3) selection

Feature extraction is a procedure which computes grip configurations from a description of the shape of the part to be grasped. Constraint filtering is an operation which rates a grip configuration based on a comparison with constraints imposed by the state of the environment. Selection is a decision making procedure which selects the best grip configuration for a part given a specific environment.

These three stages are implemented in a computer

program which is the AGSM. The inputs to the module are a CAD description of the shape of the part, a description of the shape of the gripper, the position and orientation of the part and a description of the task in terms of required part positioning. This approach is based upon the work of Christian Laugier and Tomas Lozano-Perez. [1,2]

1.4 - Thesis Structure

This chapter introduces and defines automatic grip selection. Several motivations are presented illustrating the need for the development of an AGSM. The basic approach to grip selection taken in this thesis is presented which consists of three stages: feature extraction, constraint filtering and selection.

In the next chapter, the application environment in which the AGSM is implemented is described. The equipment, control structure and operation of the application environment are depicted. The operation of the AGSM within the application control structure is discussed. The format used to represent the shape of parts to be grasped is also presented in chapter two.

The next three chapters detail the three stages of the AGSM, feature extraction, constraint filtering and selection. Chapter three describes the process of feature extraction both in the general case and as applied and implemented in the AGSM. Constraint filtering is the subject of chapter four, presented in a general context, then as applied to the specific case of grip selection. Grip configuration selection is described in chapter five. These chapters are structured similarly, presenting first a general perspective on the subject, then the role of the subject in this specific application and finally the implementation details.

Chapter six discusses the specifics of the computer system and language which were used to implement the AGSM. Two test cases are presented in chapter six including a description of the inputs to the AGSM and the results obtained. Conclusions, comments relevant to the effectiveness of the AGSM and potential improvements to the module are presented in chapter seven.

CHAPTER 2 - APPLICATION SCENARIO

At the National Bureau of Standards (NBS) in Gaithersburg, Maryland, research has been conducted for the past ten years in the area of computer automation in manufacturing. This research effort has resulted in the creation of the Automated Manufacturing Research Facility (AMRF) [10]. The AMRF consists of seven workstations which mill, drill, deburr, transport, assemble and inspect prismatic metal parts. A typical workstation in the AMRF consists a machine tool to perform some processing on metal parts produced by the AMRF, a gripper to grasp the parts, a robot to load and unload parts in the machine tools, one or more sensor systems to monitor operation of the workstation and one or more controllers to control the equipment of the workstation.

The NBS has developed a control architecture which is utilized to control the AMRF on seven levels. This architecture is a hierarchical, task decomposition, data driven architecture which is designed to be a task level programming system. This control architecture is used to control individual pieces of equipment as well as groups of machines which are configured as workstations.

This thesis describes the development of an automatic grip selection module based upon its intended application in the Cleaning and Deburring Workstation (CDWS). Specifically, the AGSM is going to compute grip configurations for the gripper on a robot which is loading and unloading a vise. The vise fixtures the parts for deburring. Section 2.1 describes the workstation environment and section 2.2 discusses the CAD description of the shape of parts to be grasped.

2.1 - The Cleaning and Deburring Workstation

The Cleaning and Deburring Workstation (CDWS) deburrs parts produced by other workstations in the AMRF. The CDWS is equipped with two robots, a programmable vise and a deburring grinder. This equipment is described in section 2.1.1. The workstation controller coordinates the operation of the CDWS and acts as the interface to the AMRF workcell controller. The control structure of the workstation is described in section 2.1.2. The operation of the CDWS is discussed in section 2.1.3.

2.1.1 Equipment in the CDWS

This workstation is equipped with two robots, a Unimate 2000 and a PUMA 760, a programmable orientation vise, a quick change wrist, high-speed grinder, force sensors in each of the robots' wrists and several computer controllers.

The Unimate 2000 robot is used to load and unload

parts from the vise. It is equipped with a pneumatic parallel jawed gripper for grasping parts it is loading and unloading from the vise. The gripper can be commanded to either open or closed and is neither force nor position servoed. The vise like the gripper is also a pneumatic parallel jawed device which is functionally the same as the gripper. The vise is used to fixture parts which are to be deburred by the PUMA 760.

The AGSM is used to compute two types of grip configurations in the CDWS. One grip configuration is fort the gripper on the 2000. The AGSM also determines a clamp configuration for the vise which specifies how the vise contacts the part while fixturing it for deburring.

The PUMA 760 robot is equipped with a quick change wrist to attach/detach different high-speed grinders to the robot's wrist for deburring different parts. The quick change wrist permits the robot to change grinders under programmed control without operator assistance. A force sensor is used by the 760 controller to monitor the deburring forces between the deburring grinder and the part.

2.1.2 The Workstation Control Structure

This workstation is under control of the AMRF cell controller. The workcell controller issues deburring commands to the CDWS controller and receives status feedback from that controller. The workstation controller controls the two robots, deburring equipment, and the vise. The 760 is under control of the NBS developed Real-time Control System (RCS) hierarchical control system [8]. The vise is controlled by its own NBS developed controller. The Unimate 2000 is controlled by a Unimation VAL-II control system.

The workstation world model includes static and dynamic information about the equipment and parts in the workstation. Static information pertaining to equipment includes functionality information (max feed rates, max reach, etc.), locations of equipment and relationships between actuators and sensors. Components of the world model which are dynamic include: current status of actuators and sensors such as "ready" or "locked" , values of parameters associated with grippers, robot arms and tools such as "gripper closed" or "robot moving"; and status of current tasks such as "deburring part # 12".

The world model also contains information about the parts in the workstation. Part information has static and dynamic components. Static information about parts is obtained initially from the AMRF database. This information describes the part's shape and deburring instructions. Dynamic information about the part includes its current location and orientation.

2.1.3 - Operation of the CDWS

The workcell controller routes parts which require deburring from other workstations to the CDWS. Parts are transported between workstations by an automatic guided vehicle system (AGVS). The CDWS controller accesses the AMRF database to acquire information about the part's shape and the deburring instructions for that part. The CDWS stores this information in its own world model.

Parts to be deburred at the CDWS arrive on a pallet which is loaded into a buffer by the AGVS. The 2000 picks up a part from the pallet, moves it to the vise, inserts it into the vise, signals the vise to close, then releases the part and moves away from the vise. The 760 then deburrs the part with a high-speed grinder following a deburring path which is planned by the deburring process planner. The deburring path is expressed as a list of edges which are to be contacted by the deburring grinder. The deburring process planner is resident in the workstation controller. Upon completition of the deburring the 2000 grasps the part in the vise, the vise releases the part and the 2000 transfers the deburred part to the pallet.

2.2 - The Description of Parts to be Grasped

In the AMRF a part is described by means of linked list of topological and geometrical entities. This is a form of CAD solids modelling which is commonly called boundary representation or b-rep for short. The b-rep data which describes the shape of a part is called a "flat file" in the AMRF integrated database.

The topological components of the flat file describe the part in terms of hierarchical relationships between shells, faces, edges, and vertices. The geometrical components of the flat file define the location in space of the topological entities. Geometrical entities are surfaces, curves, and points. Fig. 2.1 illustrates the hierarchical relationships of the flat file. The topological entities describe how the part is put together and the geometrical entities describe where the topological entities exist in space.

A very simple example of a flat file is the description of the shape of a cube expressed in boundary representation. The b-rep description of a cube consists of one shell which is composed of 6 faces. Each face is defined by a single loop of edges on a surface which in the case of a cube is a plane. Each loop consists of four edges. Each edge is defined by two vertices and the curve which connects them. In the case of the cube the curves are lines characterized by slope and intercept. Finally each vertex is defined by a point which is the coordinates of the vertex. In the case of the cube there are eight vertices and eight points.

Figure 2.2 shows a cube with numbered faces, edges and vertices and the b-rep description of the cube. Parts

which are produced by the AMRF are similarly described in the database. The b-rep description of the cube is contained in Appendix A at the end of this thesis.

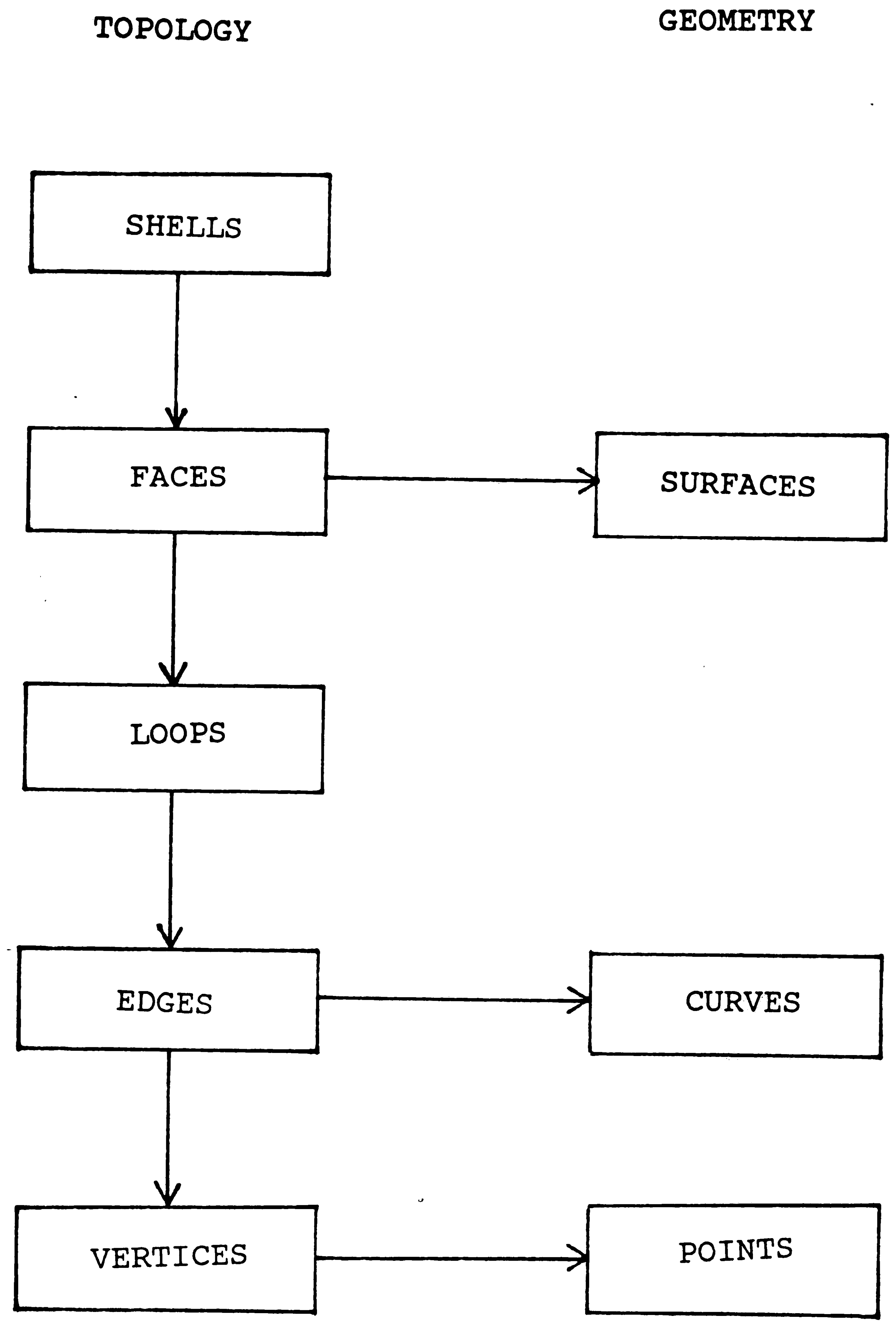


Figure 2.1 - Flat File Hierarchy

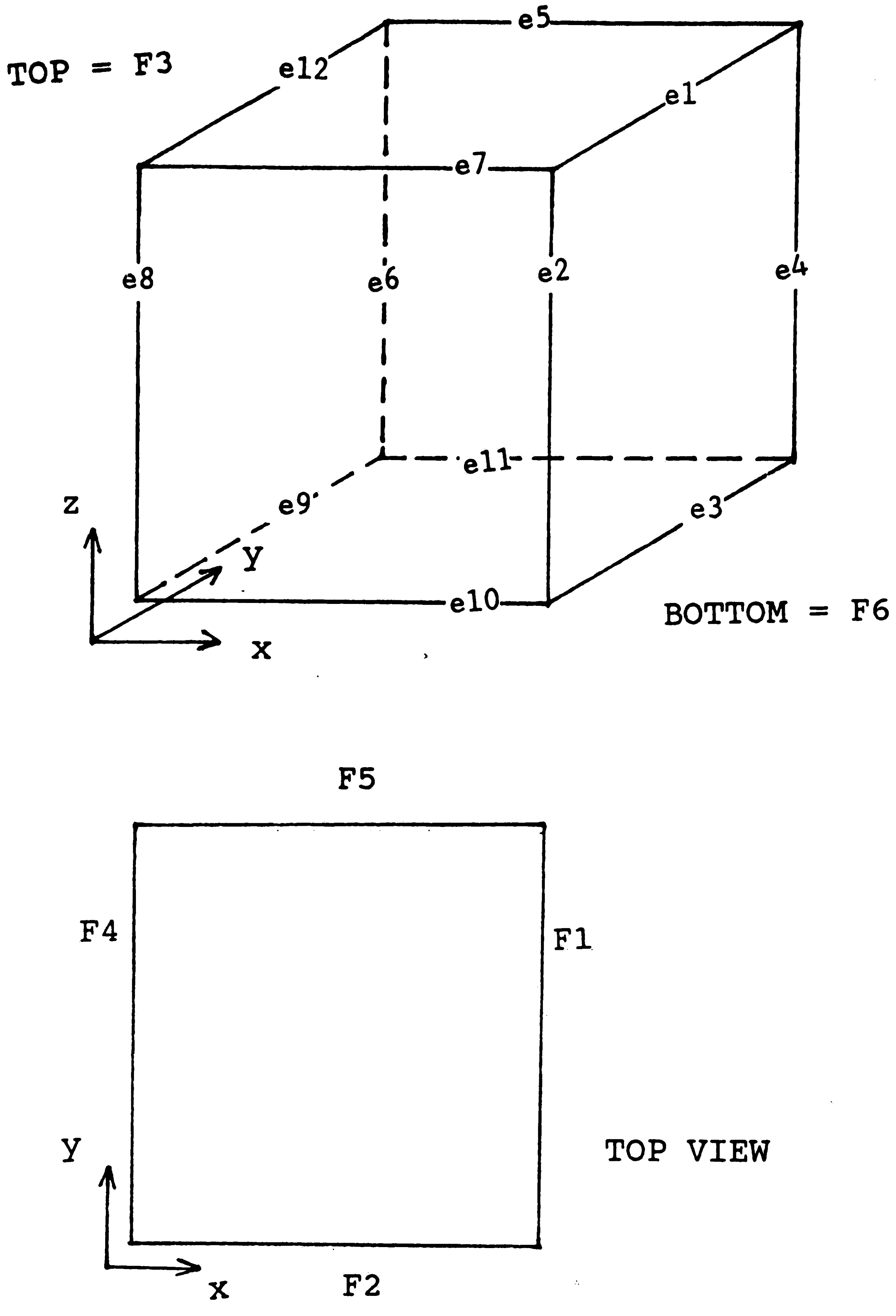


Figure 2.2 - Cube

Chapter 3 - FEATURE EXTRACTION

Features are entities which are described by a list of characteristics. A feature description is a template which has slots for the characteristics which describe that feature. Specific instances of features have values associated with the characteristics.

This chapter describes the function of, inputs to and outputs from a feature extractor. A feature extractor is a module which searches a database for instances of a particular feature. When a feature is identified, the characteristics of the feature are assigned values. The output of the feature extractor is a set of characterized features.

This chapter is organized into three major sections. In the first section generic feature extraction concepts are described. Application of feature extraction to the problem of automatically selecting a grip configuration is discussed in section 3.2. Implementation of feature extraction in the AGSM is described in section 3.3.

3.1 - General Feature Extractor Concepts

There are three questions which are relevant in any feature extractor module. What are the "features" ? Where are the features going to be extracted from ? How are the features going to be extracted ? These questions are answered in the next three sections.

3.1.1 - What are the features ?

Features which are going to be extracted are entities which are of interest for some reason. The features of interest are characterized with the same types of attributes but different attribute values. For instance in considering a job search, the feature of interest is be a job offer. There are several characteristics of each job offer, such as position, salary, location, etc. Every job offer has a location, a salary, and a position but each job offer has different values for these attributes.

3.1.2 - Where are the features being extracted from ?

Features are extracted or assembled from a single database or multiple databases. The database(s) may contain information about the features either explicitly or implicitly from the perspective of the feature extractor. For example if the weight of an object must be less than 100 lbs. to be a feature, a database which contains objects along with its weight would be an explicit representation. An implicit representation might contain the dimensions of the object and the density of the material which the object is made from. In implicit case the weight must be calculated by a preprocessing operation before the object in question can be determined to be a feature or not.

Features can be extracted from a wide variety of sources. In the job search example, potential positions might be identified in newspaper want ads, word of mouth, recruiters, or campus interviews. It is the responsibility of the feature extractor to organize the features and to characterize them in a consistent manner. Feature data might be represented in one or even several computer databases. The feature extractor searches a database for entities which match the feature description.

3.1.3 - How are the features to be extracted ?

Responses to the this question are descriptions of the implementation of the feature extractor module. First the characteristics of a feature which make it a feature must be specified. Next the rules which are going to search the database for instances of features must be specified. These rules operate on the database(s) to build a set of features. The database(s) which contains the features is examined to see if it contains information in the correct format for the rules to operate. If the database is not in the correct form, a preprocessing step is designed to translate the database format into a representation which is suitable for feature extraction.

Features are extracted by searching the database and looking for database entities which match the feature description. In the job search example, features which are job offers, are extracted in a multi-stage process.

Potential employers must be approached, interviews taken, and letters which might contain offers must be read. At each stage, characteristics of the job offer are being observed in order to attach values to the characteristics of the feature.

3.2 - Application of Feature Extraction in the AGSM

The preceding section discussed the general functionality of a feature extractor. This section describes the application of feature extraction to problem of finding grip configurations for the purpose of grasping objects in the CDWS. First the features of interest are described, then the database from which the features are extracted is discussed. Finally the technique for extracting the features is presented in section 3.2.3.

3.2.1 - Features in the AGSM

Feature extraction in the AGSM is a process for identifying and characterizing "features" of an object which are suitable for grasping. The objects which are going to be grasped in the CDWS are metal, prismatic parts. For example, Fig. 3.1 shows a pipe clamp, a typical prismatic part produced in the AMRF.

The features which the extractor is looking for in the AGSM are grip configurations. A grip configuration is a pair of planar faces on the part which are parallel to each other and have material in-between. The pairs of faces are characterized by orientation, the centroid of the overlap, and distance between the planes. Pairs of planar faces were chosen as features because they work well with the combinations of parallel-jawed grippers and prismatic parts found in the CDWS. A grip configuration is a pair of faces which are suitable for grasping by a parallel-jawed gripper.

Each pair of faces has several characteristics, the values of which make it "feasible" or "unfeasible" for grasping by a parallel-jawed gripper. For instance, faces which are not parallel to each other are not feasible grip configurations. Once a pair of faces has been determined to be feasible for grasping several, that is determined to be a feature, pertinent parameters are computed and stored with the grip configurations. These parameters are discussed more fully in the following section.

A grip configuration describes how the gripper will contact the part. It is a set of topological entities which are geometrically feasible for supporting grasping by a two-fingered gripper. The term feasible is ambiguous and is used because what is a "feasible" grip configuration in one workstation, might be "un-feasible" in another workstation. For instance, a gripper might not be able to reach a part in one workstation because of fixture interference, but which is not a problem in another workstation.

Another example which illustrates the application specific nature of a feature extractor occurs when different grippers are being used. A feature extraction module for gathering a set of grip configurations for a gripper which is a magnet will use different grip configurations than a two-fingered gripper feature extractor would use. In the former, features would be ferrous materials while the latter is looking for parallel planar faces with material in-between.

In the AGSM, features, grip configurations, are parallel, planar faces. These grip configurations are features designed for use in the CDWS with two-fingered grippers and prismatic parts.

3.2.2 - Source of Grip Configurations in the AGSM

Grip configurations are going to be extracted from the flat file representation of the part's shape. The part to be grasped is described in the flat file in b-rep format. In the flat file, faces are represented implicitly as seen from a grasping perspective. Faces are described in terms of a surface and a set of delimiting loops (refer to fig. 2.1). Face information pertinent to grasping in the AGSM consists of face orientation, area of the face, center of the face, etc. Therefore, a preprocessing step is used to translate the shape representation into a representation which is more suited to gripping. The methodology for feature extraction is described in the following section.

3.2.3 - Approach to Feature Extraction in the AGSM

Features extraction in the AGSM is accomplished in a three step procedure consisting of preprocessing, identification and characterization. The first step in the extraction process is to preprocess the raw part shape data into a format which is more suited to feature extraction than the raw data. The feature identifier searches the output from the preprocessor looking for instances of features. Once a pair of faces has been identified as a feature, the values of the characteristics of that feature are established.

Feature identification is implemented as a series of rules which check every possible pair of faces to see if they meet the definition of a feature. The rules which are used to identify features are specifically tailored to gripping parts in the CDWS with parallel jawed grippers. These rules are described in detail in section 3.3.2.

The rules for determining features are heuristic in nature and specific to a particular environment. The system implementer chooses what set of entities constitutes a suitable grip configuration. These rules would be best written by a gripper expert or fixture expert, someone with the specific mechanical engineering skills important in gripping operations. What this system attempts to do is to get the structure in place and the structure functioning, so that more detailed work in the gripping task specific area can be implemented.

The feature extractor identifies the complete set of features by which the part can be grasped based upon the logic inherent in the feature extractor. The term inherent is used here to accentuate the fact that criteria for selecting grip configurations is not external data, but internal programmed logic. The magnetic gripper case described in section 3.2.1 has a different set of rules than those for a parallel jaw gripper.

The set of features which is organized by the feature extractor is referred to as the set of "theoretical" configurations. These grip configurations are based solely upon the interpretation of the workpiece's shape and the logic of the gripper functionality. These grip configurations do not take into consideration the dimensions of gripper or the practicality of the configuration.

3.3 - Implementation of Feature Extraction in the AGSM

Grip configurations are derived from the description of the part's shape which in this case is the flat file. Before any features are extracted, the flat file data which describes faces is organized into a structure which is more oriented to grasping than the boundary representation. Since the features consist of pairs of faces, the reorganization will be in terms of faces.

Next the set of faces will be used by the feature identifier to obtain pairs of faces which are grip configurations for a parallel jawed gripper. Once a pair of faces has been identified, the values of the characterization parameters are set in the feature characterization step.

The feature extraction algorithm presented in this thesis involves three steps:

1) preprocessing
2) feature identification
3) feature characterization

The implementation of these three steps is discussed in the following sections.

3.3.1 - Preprocessing

The flat file contains a hierarchy of linked topological and geometrical entities (refer to fig 2.1). The preprocessor will organize a list of planar faces and parce the flat file representation to derive characteristics about those faces. This operation is analogous to ordering a list of addresses by zip codes in preparation for determining the population of each postal zone. First the data is organized then the operation of interest performed.

The preprocessor builds a list of faces, the members of which are planar faces. As a face is determined to be a member of this list several parameters are computed which

further characterize the face. Parameters which characterize the faces are: 1) the orientation and location of the face; 2) the centroid of the face; and 3) the vertices of the face. In a more complex part this set of parameters would have more members and a greater range of values.

The orientation of the face is encoded according to which of the axial planes the face is parallel to and which side of the face is the material side. The distance from the origin is stored as the location of the face. A set of pointers to the vertices of the face is built. The centroid of the face is computed and stored. The structure which is used for representing faces in the AGSM is shown below:

```
face_name {
   orientation
   location
   vertices_ptr[]
   centroid (x,y,z) }
```

The output of the preprocessor is an array of face structures.

3.3.2 - Feature Identification and Characterization

The set of grip configurations, pairs of faces, is constructed by picking one face then searching the rest of the list of faces for a face which has the same orientation, and material in-between. When a face is found which meets these criteria, the faces' centroids are compared to determine whether the faces are opposite each other. As long as the centroids are within an appropriate distance of each other based upon the size of the gripper fingers, the faces are considered opposite. At this point the pair of faces is identified as a feature and becomes a grip configuration.

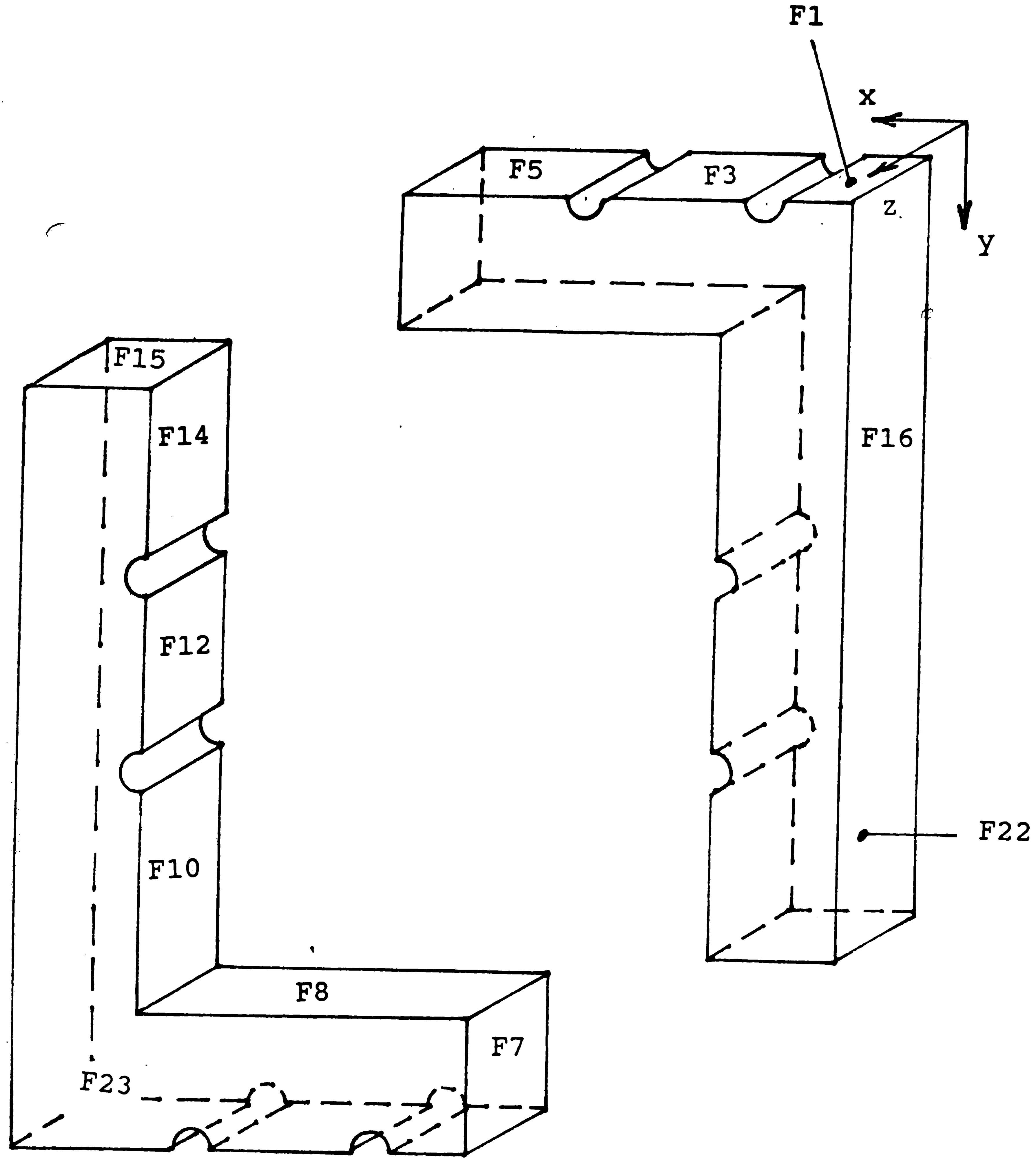
Once a pair of faces has been observed to meet the feature definition criteria, several feature parameters are computed and initialized. The average of the two centroids is computed and stored for use in developing the transformation relating the gripper to the grip configuration. The width between the pair is also computed for use later in the constraint filtering. The orientation of the pair is stored encoded based upon parallelism to one to the coordinate planes. A flag which is used for tracking the pair of faces through the constraint filters is initialized.

A global score is a measure of overall feature attributes and serves to differientiate grip configurations. The initial global score is computed as the reciprocal of the distance between the pair's centroid and the part's centroid, thus the closer a pair is to the part's centroid, the higher the global score. The global score is used to quantify a grip configuration's potential for rotation while grasped. It is desirable to grip a part as close as possible to the centroid.

The structure which is being used to represent the features or grip configurations is shown below:

```
pair_name {
    face_1_name
    face_2_name
    orientation
    center
    width
    failure_flag
    global_score  }
```

At this point the set of features, pairs of parallel, planar faces with attached characterization parameters, is passed on to the constraint filters.



surface 19 defines face 23

surface 8 defines faces 10, 12, 14

Figure 3.1 - Clamp pipe

Chapter 4 - CONSTRAINT FILTERING

Constraint filtering is defined and described in this chapter, first in the general case and next in terms of how it is used in the AGSM. In the last section in this chapter, the specific implementation details are discussed.

4.1 General concepts of Constraint Filtering

Constraint filtering is a process for applying constraints upon a set of features for the purpose of determining which features are within the constraints and therefore useful in the constrained environment. The constraint filtering process compares feature characteristics, either individually or globally, with constraint criteria. This comparison can be thresholded for a pass/fail type of comparison or the difference between the feature characteristic(s) could be saved for evaluation at a later stage. The set of features input to a constraint filter are "theoretical" features while those features which are not failed or eliminated are "practical" features, applicable to the constrained environment.

As stated above, there are two approaches to constraint filtering, pass/fail comparisons or scoring the feature based upon nearness to the constraint criteria. The pass/fail approach is used whenever it is critical that a feature be within a constraint. Constraint filtering applied in the context of the job search example might compare a specific offer with a desired salary. In the pass/fail approach, an offer below the desired salary is failed and will not be considered further.

An alternative to the pass/fail approach to constraint filtering is to update a "score" associated with each feature. This approach provides a sensitivity which is lost with the pass/fail approach at a cost of maintaining and updating the "score". Applying the scoring approach to the job search example means computing the difference between desired salary and offer salary and storing it with the job offer for consideration at a later operation. A benefit of this method is that as other characteristics are evaluated against other constraints, the "global score" associated with each feature is updated reflecting the feature's overall adherence to the constraints. Thus in the job offer example, an offer's nearness to a desired locale is coputed and added to the global score to combine a comparison of two characteristics to the constraints.

The order in which the constraints are applied to the features has no effect upon the score, but optimized sequencing of the filters could speed up the processing of the whole set. That is if a feature clearly violates a critical constraint, it makes no sense to score it further in later filters. This approach is a hybrid combination of the two approaches discussed above. This is analogous to

using coarse filters to remove debris which will clog finer filters.

In the job search example, a coarse filter might be applied to eliminate from further consideration jobs which violate fundamental constraints. A coarse constraint might be that the job location must be within one hundred miles of the beach. If an offer location is greater than one hundred miles from the beach, then that offer will not be considered further. This elimination simplifies and shortens the search time.

4.2 - Constraint Filtering in the AGSM

The feature extraction portion of the AGSM produces a set of candidate grip configurations which is the complete set of ways the part can theoretically be grasped. It is the job of the constraint filter to impose real world conditions, constraints, to the theoretical set and produce a set of configurations which will work given the current state of the workstation. The set of theoretical configurations is "filtered" to produce a sub-set of configurations which are called "practical" configurations. In the AGSM features are passed or eliminated rather than scored as described above. This is a result of the critical nature of the simple constraints which are implemented in the AGSM.

The set of theoretical grip configurations is intended for use with a parallel jawed gripper. The AGSM is being applied in the CDWS where it is necessary to determine grip configurations for two parallel jawed devices: a gripper on the robot used to transfer the parts and a vise which is used to fixture those parts. Both of these devices are functionally equivalent and therefore the output of the feature extractor, theoretical grip configurations, is equally applicable to both devices.

The constraints imposed upon theoretical grip configurations for the gripper are different than the constraints imposed upon theoretical clamp configurations. Thus it is necessary to create two separate sets of configurations, one set for the gripper and one set for the vise. The duplication of the feature extractor output is the first operation in the constraint filter module in the AGSM. The set of configurations for use by the vise are called "clamp configurations".

Figure 4.1 shows a diagram of the constraint filtering module as implemented in the AGSM. Two sets of theoretical grip configurations are produced initially setting the stage for two initially identical sets of configurations to be filtered in parallel. Grip configurations are filtered against constraints imposed by the robot gripper and by the initial orientation of the part. Clamp configurations are filtered against constraints imposed by the vise and by the task required final position of the part in the vise.

The output of the constraint filter module is two sets of practical configurations, one for the gripper and one for the vise. The selection module chooses one practical grip configuration and one practical clamp configuration for use and sends these to the workstation.

Gripper constraints

Theoretical grip configurations are filtered against two criteria. The first constraint filter checks each feature against gripper criteria to make sure that the gripper can grasp the feature. Gripper constraint criteria is derived from a description of the gripper located in the CDWS world model. Next the features which made it past the gripper filter are evaluated on the basis of the way the part is oriented in the workstation environment. The position and orientation are available from the CDWS world model. Features which make it past this filter are practical grip configurations.

Vise constraints

Theoretical clamp configurations are filtered against two criteria. Vise constraints are applied to the set first in the same way that the gripper constraints are applied to the set of grip configurations. Vise constraints are derived from a description of the vise in the CDWS world model. Final position constraints are imposed based upon the deburring path requirements. The deburring path is specified in terms of which edges need be exposed for deburring. Clamp configurations are checked for interference with the deburring path and eliminated from further consideration if interference is possible with the deburring path. Features which make it past these two filters become practical clamp configurations.

4.3 - Implementation of Constraint Filtering in the AGSM

This section describes how constraint filtering has been implemented in the AGSM. Two parallel constraint filtering paths are discussed, one path which filters grip configurations in section 4.3.1 and the other path which filters clamp configurations in section 4.3.2. As previously stated, the pass/fail approach to constraint filtering is implemented in the AGSM because simple constraints impose a pass/fail comparison strategy. The approach is implemented by means of a flag associated with each configuration. If a configuration is determined to lie outside a constraint, the flag is set to reflect failure. The configuration continues to be evaluated by any subsequent filters which also update the flag in a way which preserves the configurations pass/fail history. This provides a useful debugging tool for evaluating the performance of the constraint filtering module.

4.3.1 - Filtering Grip Configurations

Grip configurations are compared against constraints imposed by the functionality of the gripper and by the

initial orientation of the part, that is where the part is to be grasped. The entire set of theoretical grip configurations is evaluated against gripper constraints as a batch, then against initial orientation constraints as a batch. Gripper functionality is characterized by maximum and minimum opening widths since the gripper can only be commanded to be open or closed. Initial orientation is characterized as describing to which of the axial planes the part is parallel.

Theoretical grip configurations are first filtered against gripper constraints as seen in fig 4.1. The width of the grip configuration is compared with the maximum and minimum gripper opening. Configurations which are wider than the maximum gripper opening are tagged "Too-wide", while those which are narrower than the minimum gripper opening are tagged "Too-narrow". These configurations cannot be grasped by the gripper. The tagging takes place in the form of setting the configuration's failure flag with a coded value associated with "Too-wide" or "Too-narrow".

Next grip configurations are evaluated against constraints imposed by the initial orientation of the part to be grasped. This comparison is accomplished by comparing the orientation of the grip configuration, characterized like the initial orientation by which part plane the configuration is parallel to, and setting the configuration's failure flag to "Bad_orientation". These grip configurations cannot be grasped by the gripper because they are parallel to the surface on which the part is resting.

4.3.2 - Filtering Vise Configurations

The set of theoretical clamp configurations, identical to the set of theoretical grip configurations, is filtered against constraints imposed by the vise and constraints imposed by the required final position of the part in the vise. The whole set of clamp configurations proceeds through the vise filter first then through the final position filter.

Vise operation is characterized in the exact same way as with the gripper described above. Thus the width each clamp configuration is compared with the maximum and minimum opening width of the vise. If the configuration violates either constraint it is tagged appropriately.

Final position constraints are represented as a surface which must be exposed in order to be accessible to the deburring tool. Clamp configurations are eliminated, via failure flag, if they use a face which must be exposed for deburring. Faces which violate this criteria are tagged "Deburring_interference".

4.3.4 - Output of the Constraint Filters

At this point there exists two sets of practical

features, a set of practical clamp configurations for the vise and a set of practical grip configurations for the gripper. The term practical is used here to indicate that these features have been checked for compliance with constraints imposed by the configuration and state of the workstation. Both sets of features are ranked by a goodness index which has been updated by the constraint filters.

4.4 - Summary

In this chapter, the driving principles of constraint filtering are presented and three approaches for implementing a constraint filtering module. The first approach is the simple pass/fail method of limited sensitivity and ease of implementation. The second approach involves evaluation and "scoring" a feature based upon nearness to the constraint criteria. The third approach is a combination of the other two approaches whereby critical constraints are used to "trim" features which violate the critical criteria while scoring features against other non-critical characteristics.

It is worthwhile to mention here what the meaning of an empty set of practical features, that is no practical grip or clamp configurations, implies. This "total filtering" is caused by one of two basic reasons. Either there exists no practical grip configurations for a particular part with a particular gripper or the combination of feature extractor and constraint filters is not matched. In the first case the AGSM is functioning correctly and there is no way to grasp the part with the current gripper.

In the latter case, the feature extractor and the constraint filters have not been designed correctly. If this happens the system designer must reexamine both modules, checking the logic in each. The system designer need determine what kind of features are coming out of the feature extractor, then determine what features are being eliminated by the constraint filters and by which constraint. The failure flag attached to each feature and set by the constraint which fails the feature is a useful debugging tool in this situation.

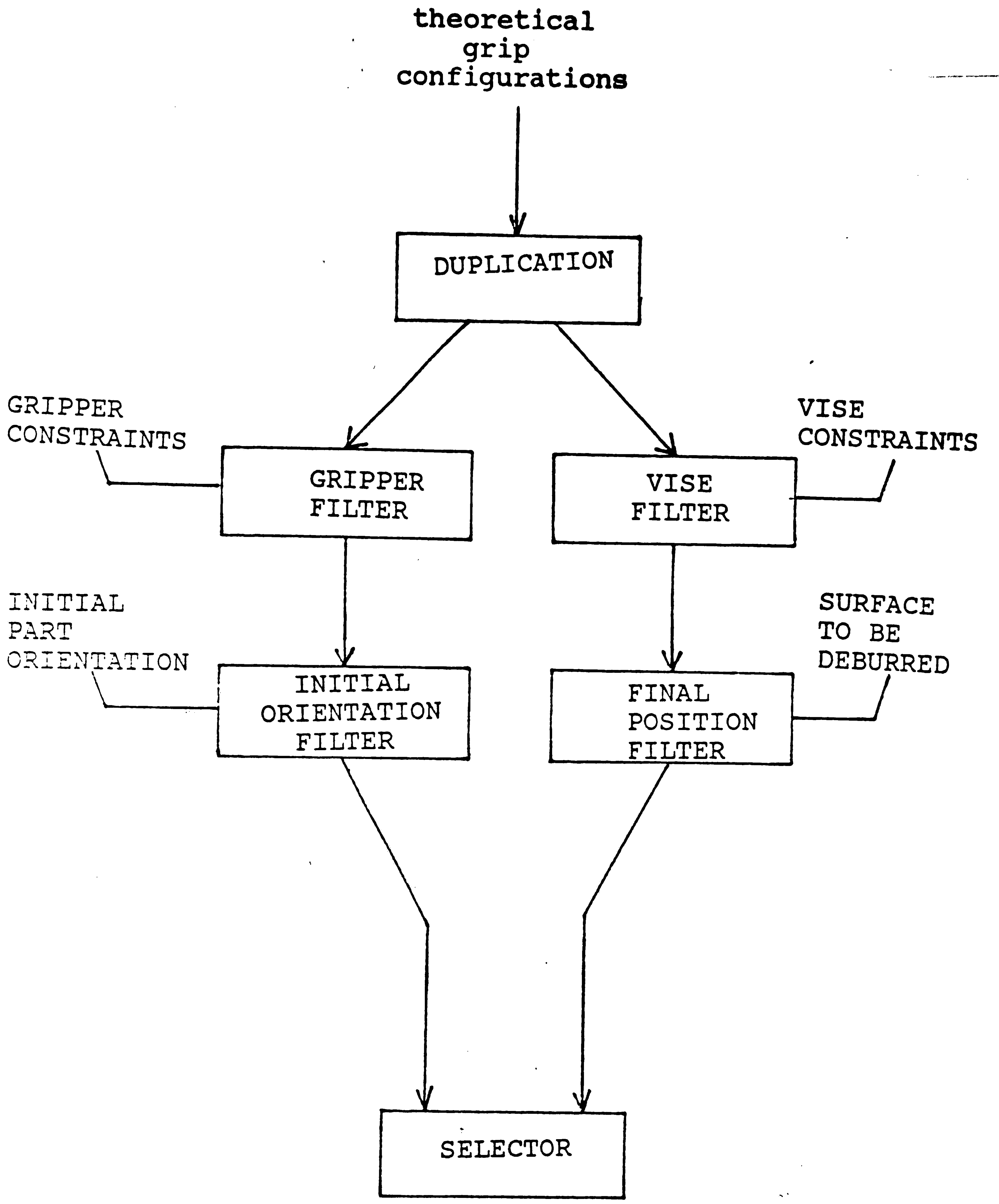


Figure 4.1 - Diagram of Constraint Filtering

Chapter 5 - SELECTION

At this point in the operation of the AGSM, there exist two sets of practical features, grip configurations and clamp configurations. It is now necessary to choose a grip configuration for use by the robot controller to pick up a part and a clamp configuration for use by the vise controller to fixture the part to be deburred. The selection process performs this task in the AGSM. General concepts of selection are described in section 5.1. Application of selection to the AGSM is described in the next section.

5.1 - General Selection Concepts

The selection process is a decision making process whereby a particular member of a set of features is chosen for use. The feature extraction module identifies a set of theoretical or candidate features. The constraint filter eliminates (or scores) theoretical features which do not lie within constraints imposed by the environment for which the features are to be used.

In the case where features are eliminated if they violate constraint criteria, the selection process consists of simply choosing a feature which is not eliminated. In the case where constraint filtering updates a global score reflecting a feature's overall nearness to constraint criteria, the selection process consists of choosing the feature with the best global score.

5.2 - Selection in the AGSM

After the constraint filtering module has operated on the theoretical grip configurations there exists a set of practical grip configurations and a set of practical clamp configurations which are achievable in the environment described by the CDWS world model. The selector module of the AGSM chooses a grip configuration and a clamp configuration which will work in conjunction with each other. The selector module combines the parallel paths of the constraint filtering module so that conflict between configurations is resolved.

The selector picks the best clamp grip configuration first based upon global score set in the feature extractor module. Next the selector attempts to choose the best configuration for the gripper, again based upon the configuration. It compares the best gripper configuration with the chosen clamp configuration for interference. If there is no interference then the pair of configurations is chosen for use. In the event that there is some interference an alternate selection must be made. Interference is characterized in the AGSM by the same pair of faces being chosen for gripper and vise.

There are several options if interference between the two configurations is detected. The selector could look at the second clamp configuration and compare it to the first gripper configuration. Or the selector could stick with the best clamp configuration and check the second best grip configuration.

In this implementation, the selector attempts to keep the best clamp configuration and looks further into the list of gripper configurations. In the event that no gripper configurations exist which do not collide with the best clamp configuration the selector signals a failure.

The selected grip and clamp configurations are now sent to the workstation controller for use in grasping the part with the gripper and clamping the part with the vise. The selector sends the grip and clamp configurations in the form of a location and an orientation. The location is the centroid of the pair of planar faces. The orientation is specified as the axial plane which characterizes the pair of faces.

5.3 - Summary

Selection is the process of choosing a feature from a set of features for use in a task. The selection process is greatly simplified if a global score is attached to each feature. In the case of the AGSM, where a global score is attached and features have been filtered with the pass/fail approach discussed in chapter four, selection involves

identifying the feature with the highest global score and a failure flag which indicates that the configuration has passed successfully through the constraint filters.

The selection module in the AGSM is the function which combines two configurations in order to accomplish the task of grasping a part and inserting it into the vise for fixturing. The two configurations, a grip and a clamp configuration, have the potential for interference which the selector rectifies by choosing the clamp configuration first, then determining the best non-interfering grip configuration.

In the next chapter the implementation of the AGSM is described in detail as well as the effectiveness of the module in operation.

Chapter 6 - AGSM IMPLEMENTATION AND OPERATION

In the previous three chapters, an approach to automatic grip selection is presented. That approach, implemented in the AGSM, consists of three stages: feature extraction, constraint filtering and selection. It is relevant to experiment with the AGSM in order to characterize and calibrate its performance. Describing the method of experimentation and the results of that evaluation are the purposes of this chapter.

The implementation environment within which the Automatic Grip Selection Module (AGSM) is implemented is described in section 6.1. The AGSM is applied to two different parts for the purpose of observing the effectiveness of the approach. The two parts are analyzed by the AGSM in order to determine practical grip and clamp configurations for two different orientations and deburring paths. Specific information about parts, gripper and vise are described in section 6.2. Results of the experiments are presented in section 6.3 and interpreted in section 6.4.

6.1 - Implementation Environment

The AGSM described in this thesis was implemented on a Zenith IBM PC/XT compatible computer. The AGSM was coded

in 'C' using the C-TERP interpretive development environment. There are five major modules which comprise the AGSM. These modules are listed and described below. The results are expressed as outputs from these modules.

PARSER - reads the flat file and produces arrays of faces, loops, edges, surfaces, and points.

FACER - builds an array of face structures which are grasp oriented from the flat file structures. The grip oriented face structures are described in section 3.3.1. FACER performs the preprocessing operation on the raw flat file data.

EXTRACTOR - identifies and characterizes grip configurations from the array of face structures produced by FACER. EXTRACTOR produces an array of theoretical grip configurations which are characterized by orientation, location and global score.

FILTER - filters one set of theoretical grip configurations and one set of theoretical clamp configurations. The grip configurations are filtered against constraints imposed by the gripper and part orientation. The clamp configurations are filtered against constraints imposed by the vise and the final position of the part.

SELECTOR - chooses the best clamp configuration and the best grip configuration which do not interfere with each other and have not been elimiated by the constraint filters. The clamp and grip configurations are ranked on the basis of their global score.

6.2 - Description of Input Data

Two part are used to determine the effectiveness of the AGSM in finding grip and clamp configurations. The cube shown in figure 2.2 is one of the trial parts. The clamp pipe is an part produced by the AMRF at NBS in the fall of

1986 is the other trial part. The clamp pipe is shown in figure 3.1.

The AGSM operates on the clamp pipe for two different combinations of initial position and deburring paths. In the first case, the deburring path is specified to be surface 19 and the position is specified as being parallel to the part x-y plane. Next the clamp pipe is to deburred on surface 8 and is positioned parallel to the part y-z plane. These surfaces correspond to figure 3.1. The cube is positioned parallel to the y-z plane and surface 2 is to be deburred.

The gripper used in the test cases is a parallel jawed gripper which can open to a maximum width of 7.5 inches and close until the fingers contact each other. The gripper fingers each have gripping area of 1.5 inches by 1.5 inches. The gripper fingers are 6 inches long.

The vise used in the test cases is also a parallel jawed device which can open to a maximum width of 5.5 inches and close until the fingers contact each other. The vise fingers each have gripping area of .375 inches by 6 inches. Figure 6.1 shows the shape and dimensions of the vise and gripper.

6.3 - Trial Results

The output of the AGSM resulting from its application to the cube and clamp pipe is presented on the following page. Output from each of the major stages is shown in order to impart a perception of the scope of the part data and the results of the AGSM at the major stages. Clamp pipe (i) refers to the clamp pipe oriented parallel to the part x-y plane and surface 19 is to be deburred. Clamp pipe (ii) refers to the input conditions where the part is oriented parallel to the y-z plane and surface 8 is to be deburred. Refer to figure 3.1 for a diagram of orientations and surfaces on the clamp pipe.

OPERATION	CUBE	CLAMP PIPE (i)	CLAMP PIPE (ii)
PARSER	6 faces 6 loops 12 edges 6 surfaces 8 points	23 faces 35 loops 59 edges 19 surface 42 points	23 faces 35 loops 59 edges 19 surfaces 42 points
FACER	6 planar faces 2 x-y 2 y-z 2 z-x	12 planar faces 2 x-y 5 y-z 5 z-x	12 planar faces 2 x-y 5 y-z 5 z-x
EXTRACTOR	3 g.c. 1- f1 & f4 2- f2 & f5 3- f3 & f6 max g.i.=99.99 min g.i.=99.99	11 g.c. 1- f1 & f8 2- f1 & f15 3- f3 & f8 4- f3 & f15 5- f5 & f8 6- f5 & f15 7- f7 & f16 8- f10 & f16 9- f12 & f16 10- f14 & f16 11- f22 & f23 max g.i.=2.5 min g.i.=.35	11 g.c. 1- f1 & f8 2- f1 & f15 3- f3 & f8 4- f3 & f15 5- f5 & f8 6- f5 & f15 7- f7 & f16 8- f10 & f16 9- f12 & f16 10- f14 & f16 11- f22 & f23 max g.i.=2.5 min g.i.=.35
FILTER	g.c.#1 (1) c.c #2 (4)	g.c. #11 (1) c.c. #2,4,6 (2) c.c. #11 (4)	g.c. #7,8,9,10 (1) c.c. #2,4,6 (2) c.c. #8,9,10 (4)
SELECTOR	c.c.= #1 g.c.= #2 conflict	c.c.= #7 g.c.= #4 conflict	c.c.= #7 g.c.= #4 conflict

Abbreviations:
c.c. = clamp configuration
g.c. = grip configuration
g.i. = goodness index

Numbers in () at FILTER are failure codes:
1 - violates orientation
2 - too wide for gripper
3 - too thin for gripper
4 - uses deburring path

The PARSER module reads the flat file which describes the shape of the parts and produces a count of the various entities - faces, loops, edges, surfaces, and points. The clamp pipe is a more complex part than the cube because it is characterized by more faces, edges, etc. than the cube.

The output of the FACER module is a set of planar faces which are characterized by location and orientation. There are twice as many planar faces on the clamp pipe (12) as on the cube (6). Nearly one half (11 of 23) of the faces on the clamp pipe are non-planar. These non-planar faces are the drill holes which cut-outs and are not considered further by the AGSM.

Extractor identifies 11 pairs of faces as features, however not all of these pairs should be identified as features. Faces (3, 15) and (5, 15) do not overlap but the centroids are close enough to qualify these pairs as grip configurations. This error indicates the need for a more comprehensive overlap detector. The goodness indices indicate how close the pair centroid is to the part centroid. The cube global score is 99.99 because the pair centroids are identical to the part centroid due cube symmetry.

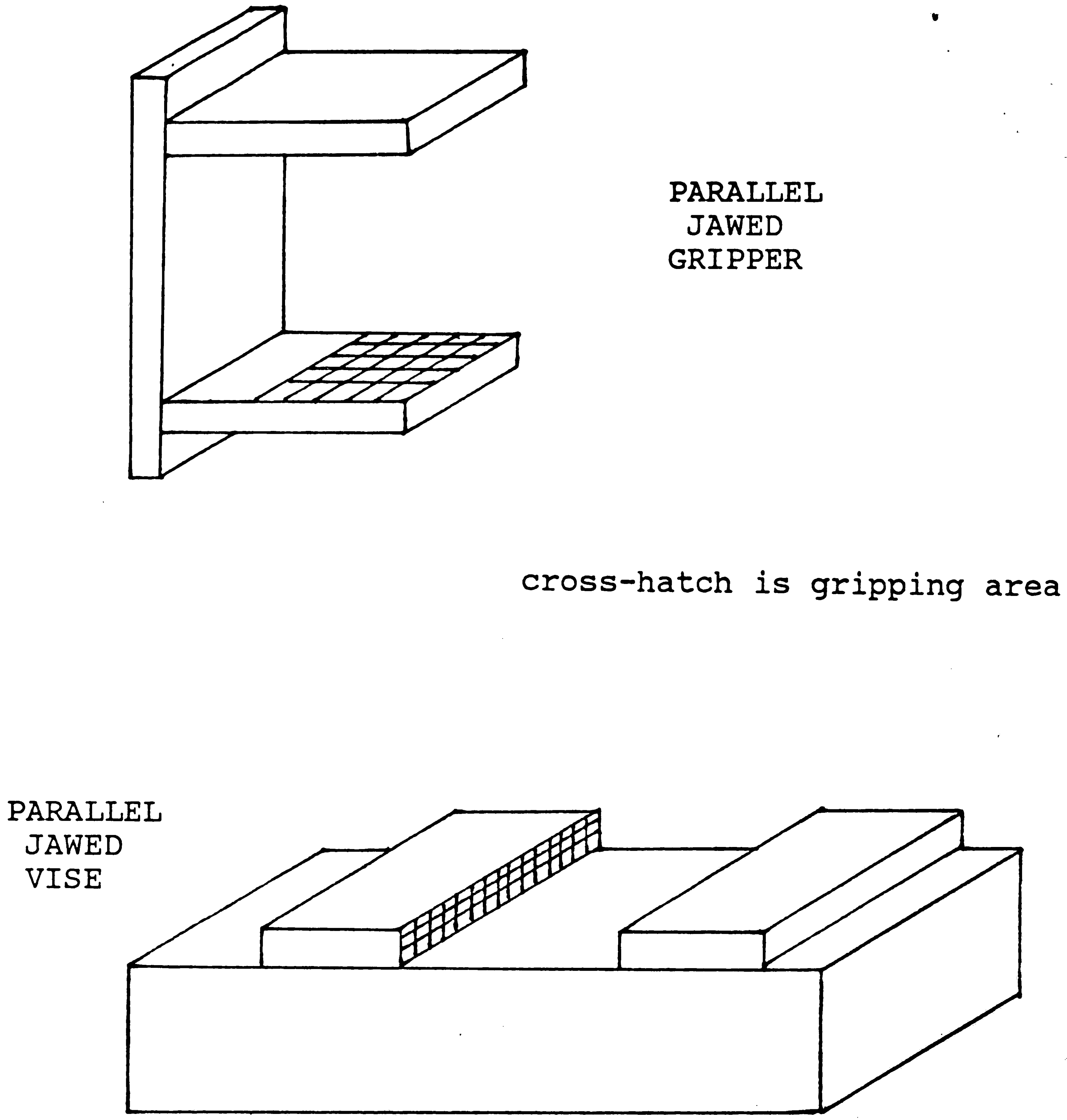
The constraint filtering operation has eliminated grip configurations because they are parallel to the initial orientation of the part (failure code = 1). Clamp configurations were eliminated as a result of two reasons: the vise could not open wide enough to accommodate that configuration (failure code = 2) or the configuration required that the vise contact a face to be deburred (failure code = 4).

The selection process selected the same grip and clamp configuration in both trials of the clamp pipe. In all cases there was conflict. This occurs because of the common origin of the clamp and grip configurations at the beginning of the constraint filtering operation. The reader is directed to figure 3.1 to observe the output of AGSM as it applies to the clamp pipe.

6.4 - Interpretation of AGSM Results

The AGSM successfully found practical clamp and grip configurations, even though the feature extractor identified several configurations which should not have been identified. For the current implemenation, if there are pairs of planar faces parallel to each of the axial planes, then the AGSM will find grip and clamp configuration which may or may not be eliminated by the constraint filters.

In the next chapter comments are presented concerning the effectiveness of the AGSM as well as suggestions for improvement.



cross-hatch is gripping area

Figure 6.1 - Gripper and Vise

Chapter 7 - CONCLUSIONS

Having presented in the preceding chapters the rationale for an automatic grip selection module, the approach, design and implementation of the AGSM, and finally the results of three test cases, it is now appropriate to comment on the effectiveness and context of the approach. This chapter is divided into three parts. First the results from the two test cases are analyzed and interpreted. Next some suggestions are presented as to how the effectiveness of the AGSM can be improved in the future. In the final section, several closing comments about the AGSM are presented.

7.1 - Effectiveness of the AGSM

Evaluating the effectiveness of the AGSM approach can be carried out to varying degrees of complexity. At the simplest level of complexity, effectiveness is characterized by the presence or absence of a practical grip and a practical clamp configuration after the AGSM has analyzed the part description. At this level the AGSM approach is effective since it did determine a grip and a clamp configuration.

An evaluation at a higher level of complexity is observing how many features, grip configurations, were identified by the feature extractor. This evaluation is a

measure of how well the feature extractor is applicable to the current part.

The constraint filters are effective so long as grip and clamp configurations which pass successfully through them are achievable. This same measure of effectiveness can be applied to the selection process: if the grip and clamp configurations chosen are achievable then the selector module is effective. These measures of effectiveness cannot be tested without trying the grip configurations with a robot or a robot simulator.

The effectiveness of the grip selection module is directly related to the complexity of the heuristic rules which are used to identify and filter grip configurations. Effectiveness is also dependent upon the application environment, that is the context of the application which is built into the module. Thus effectiveness to a degree is dependant upon the similarity of the application environment to the design environment. In the case of the AGSM, which is designed to find grip configurations on parts with planar faces, if presented with parts which do not have any planar faces, then no grip configurations will be identified by the feature extractor. Likewise the constraint filters are used to filter a set of grip configurations with widths greater than the gripper can open, no configurations will pass successfully. The design must be matched to the application.

The overall effectiveness of the AGSM is seen to reside in the architecture of the approach rather than the implementation itself. The architecture of the AGSM consists of a sequential path of feature identification, constraint filtering of identified grip configurations against constraints imposed by the application environment and selection of grip configurations based upon a global score.

7.2 - Suggestions for Improvements

This thesis has described the underlying reasons for the development of an automatic grip selection module and an approach to the design and implementation of such a module. After testing the resultant design there are several modifications which if implemented will improve the effectiveness of the automatic grip selection module.

The addition of a solids modelling system with a graphics display and an accessible model database is a critical improvement to the user interface of the automatic grip selection module. It is difficult for the system programmer to comprehend grip configurations expressed as numbers. A graphical display frees the system programmer of storing the model of the part to be grasped in his head. The graphics system will assist the system programmer in developing the rules for feature extraction and constraint filtering. It will also aid in analyzing the output of the module, as the programmer directly visualizes the results rather than interpreting topological entity identification

numbers and the positions of those entities.

The AGSM described in this thesis detects grip configurations which are pairs of parallel planar faces. The feature extractor does not consider non-planar faces, edges or points in its search for features. This limited scope is inherent in the rules which are used to find features. By modifying the feature extractor rules to consider non-planar faces, edges and points as potential grip configurations the AGSM becomes more robust and powerful, able to find grip configurations on more complex parts. The improved AGSM with expanded reasoning powers can determine grip configurations which would not be identified by the current implementation.

Another conceivable improvement to the AGSM is a module which checks grip configurations for interference between the gripper fingers and the part. For instance, if the gripper is going to grasp a face which is one side of a slot, the finger width must be less than the width of the slot for an interference free grip configuration. An interference checker module checks each grip configuration, eliminating those which have obvious interferences, and scoring other grip configurations based upon their potential for interference.

A further improvement of the AGSM involves a detailed consideration of the mechanical factors of grip configuration such as part moments while being grasped, slippage while being grasped, required force of grasp, etc. The consideration of these mechanical aspects of grip configurations are computed in the constraint filtering process and incorporated into the goodness index as well as being attached to the feature. This improvement implies a more comprehensive representation of the gripper, including such quantities as frictional coefficients of the fingers and a more comprehensive representation of the part, including such parameters as surface finish and material properties.

7.3 - Final Comments

The automatic grip selection module presented in this thesis is seen as a viable architecture for selecting practical grip and clamp configurations for use with prismatic parts with parallel jawed devices. This implementation demonstrates that the three stage approach, feature extraction, constraint filtering and selection, is effective but with the limited reasoning power inherent in each of stages, this AGSM can only determine grip configurations for rather simple parts. More comprehensive modules with greater reasoning capability are necessary for grip selection on more complex parts. A solids modelling system is seen as a critical addition in the development of a automatic grip selection module.

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Appendix A - Example of a flat file for a cube

```
/PART_MODEL
/HEADER
    PART_NAME = ' Cuboid ' .
/END_HEADER

/TOPOLOGY
/SHELLS
    s1; f1, f2, f3, f4, f5, f6 .
/END_SHELLS
/FACES
    f1;   loop1;         S1 + .
    f2;   loop2;         S2 + .
    f3;   loop3;         S3 + .
    f4;   loop4;         S4 + .
    f5;   loop5;         S5 + .
    f6;   loop6;         S6 + .
/END_FACES
/LOOPS
    loop1; e1 +, e2 +, e3 +, e4 + .
    loop2; e10 +, e8 +, e7 +, e2 + .
    loop3; e1 +, e5 +, e6 +, e7 + .
    loop4; e9 +, e8 +, e6 +, e12 + .
    loop5; e11 +, e12 +, e5 +, e4 + .
    loop6; e9 +, e10 +, e3 +, e11 + .
/END_LOOPS
/EDGES
    e1; v1, v4; C1 + .
    e2; v2, v1; C2 + .
    e3; v3, v2; C3 + .
    e4; v4, v3; C4 + .
    e5; v5, v4; C5 + .
    e6; v6, v5; C6 + .
    e7; v1, v6; C7 + .
    e8; v7, v6; C8 + .
    e9; v8, v7; C9 + .
    e10; v7, v2; C10 + .
    e11; v8, v3; C11 + .
    e12; v5, v8; C12 + .
/END_EDGES
/END_TOPOLOGY
/GEOMETRY
/SURFACES
    S1;    PLANE;    1.0,      0,      0;  5.0 .
    S2;    PLANE;      0,   -1.0,      0;  0.0 .
    S3;    PLANE;      0,      0,    1.0;  5.0 .
    S4;    PLANE;   -1.0,      0,      0;  0.0 .
    S5;    PLANE;      0,    1.0,      0;  5.0 .
```

```
    S6;   PLANE;      0,      0, -1.0;  0.0 .
/END_SURFACES
/CURVES
/END_CURVES
/POINTS
    P1;   5.0, 0.0, 5.0 .
    P2;   5.0, 0.0, 0.0 .
    P3;   5.0, 5.0, 0.0 .
    P4;   5.0, 5.0, 5.0 .
    P5;   0.0, 5.0, 5.0 .
    P6;   0.0, 0.0, 5.0 .
    P7;   0.0, 0.0, 0.0 .
    P8;   0.0, 5.0, 0.0 .
/END_POINTS
/END_GEOMETRY
/END_MODEL
```

VITA

Michael Connolly was born in Pittsburgh, Pennsylvania to Lawrence and Doris Connolly on May 5, 1960. He attended the University of Pittsburgh where he received his Bachelor of Science degree in Electrical Engineering in April 1982. Upon graduation from Pitt, he was employed by Westinghouse Electric Corporation at the R&D Center in Pittsburgh for three years.

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Automatic Grip Selection
by Michael L. Connolly

ABSTRACT

As companies pursue Computer Integrated Manufacturing in an attempt to build flexible manufacturing systems, robots are being used in a variety of material handling operations. Robots in these applications need to have the flexibility to deal with an assortment of parts without being taken out of production or reprogrammed. This thesis describes an approach to automatically determining the way a robot should grasp a part given a CAD description of the part's shape. The approach which is presented enables the robot to be flexible in that parts which have not been grasped previously can be grasped successfully without taking the robot out of production or modifying existing robot programs.

The approach to automatic grip selection consists of three major steps: feature extraction, constraint filtering and selection. Feature extraction is a process for identifying all instances of grip configurations from a CAD description of the part to be grasped. A grip configuration describes how the gripper should contact the part in order to grasp it successfully. Constraint filtering imposes real world conditions upon a set of grip configurations, eliminating those which are not appropiate for the current state of the environment. Selection is a decision making process in which a grip configuration is selected for use based upon a measure of its applicability to both the part and the environment.

The approach to automatic grip selection presented in this thesis is implemented in the Automatic Grip Selection Module (AGSM). The AGSM is evaluated in two trial cases based upon its performance. The approach is seen to be an effective architecture for grip selection, capable of supporting the implementation of more comprehensive modules for grasping more complex parts.