Feasibility of a Flexible Fixturing System

By

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A Thesis/Practicum submitted to the Faculty of Graduate Studies of The University of Manitoba in partial fulfillment of the requirement of the degree

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Abstract

Fixturing of parts during manufacturing operations traditionally relies on the knowledge and experience of the operator. Typically the operator positions the part, performs the operation and reconfigures the setup for the next operation. This research demonstrates the feasibility of a flexible fixturing system capable of dynamically reconfiguring. Several examples of machining a 2D part are illustrated. Specifically, the problem of restraining planar parts during 2 ½ D milling is examined.

The experimental setup simulates automated clamping in a milling environment. The part is restrained using four top clamps each with two degrees of freedom. The algorithm determines clamping locations for each of the clamp arms, and controls the clamping system during operation. During machining, if one of the clamps interferes with the milling tool, it is relocated to a predetermined safe location until it no longer interferes.

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Chapter 1 Introduction

1.1 Motivation

The manufacturing of parts and components is increasingly becoming more automated. Actual processing times have been reduced substantially as a result of the use of computerized machine tools. Robots can also be used to quickly transfer parts between machines. However, one of the issues that still needs to be improved is the setup time. The setup time is defined as the time required to start producing a part after it has been initially designed. If the batch size is sufficiently large, the setup time required to develop, debug and ramp up the manufacturing system is comparatively less than the processing time. With smaller batch sizes the setup time becomes very significant. One of the main contributors to the setup time is the design and development of fixtures. Indeed, a fixture needs to be custom designed and built to a tight tolerance for many parts. These dedicated fixtures are expensive and they may only be useful for a specific part. For large batches, the cost of a fixture is relatively small per part. However, for small batches, the cost of the fixture is quite large per part. Hence, it is clearly very desirable to focus on the development of flexible fixtures that will reduce the overall setup time.

1.2 Scope

The aim of this research is to develop a working model of a flexible fixturing system. To accomplish this goal, the data representing the geometry of a part and the toolpath information is processed using software based algorithms. The software determines appropriate clamping positions, and intermediate positions that the clamp will move to whenever a potential collision between the tool and a clamp is detected by the software. The algorithm then incorporates dynamic control of a custom developed fixture developed for the purpose of demonstrating the effectiveness of the proposed methodology in machining applications. It is unlikely, however, to develop one generic fixture that is capable of holding all part geometries under all machining situations. On the other hand, the fixturing system should be capable of restraining a family of similar parts. The family that is examined in this research consists of planar parts that require milling operations. Such situations are common in manufacturing.

1.3 Organization

The format of the thesis is described next. First a brief review is provided of the current literature in flexible fixturing. Then an analysis is given of the adopted clamping configuration strategy. This is followed by a description of the hardware and software that make up the flexible fixturing system, followed by a description of the interaction between the milling machine and clamping system. Next, the results of different examples are examined in order to identify strengths and weaknesses of the approach. Finally, conclusions and recommendations are provided.

Chapter 2 Literature Review

Much research has focused on fixtures and design for automation during the past twenty years. This research is motivated by the potential savings that flexible fixtures realize. They reduce the number of required dedicated fixtures [1]. The research can be separated into two broad fields: analysis related to the appropriate selection of clamping positions and issues related to the mechanical design of flexible fixtures. The fields are closely interrelated and, hence, there is appreciable overlap in the material covered. It is unreasonable to look at a fixturing strategy without considering the hardware that is to be used.

2.1 Automated Fixture Design

The intention of automating a fixture is to minimize human intervention in the fixture development process. A fixture design consists of identifying clamping and locating points on a part as well as identifying a suitable mechanical design. These points are determined using such criteria as locating accuracy, restraint of the part, limited deformation, and no machining interference [1]. There are several different approaches to the fixturing problem. The first method that will be described uses lattice style, modular fixtures and examines the part geometry to determine a solution. A second approach uses the 3-2-1 locating principle to determine the clamping configuration. Related research incorporates artificial intelligence techniques to improve the fixturing algorithms.

Modular fixtures are one of the most commonly used solutions in industry. Brost and Goldberg [2] presented an algorithm for determining all the possible clamping configurations for a modular clamping system composed of a lattice of precisely spaced holes with an assortment of locating and clamping modules. Their algorithm applied three round locators centered on a lattice point and a translating clamp for a polygonal planar part. The optimal clamping configuration was proposed based on a specified quality metric.

The previous algorithm was extended by Brost and Peters [3] to hold three dimensional parts. The new algorithm broke the analysis into two parts. The motion within the xy plane was constrained using locators and a side clamp as described in the previous algorithm. Top clamps were utilized to prevent an out of plane motion.

A different algorithm, proposed by Wallack and Canny [4], utilized a fixture vice to restrain two and a half dimensional, polyhedral objects. A fixture vice consists of modular fixture elements (pegs) placed in a lattice of holes mounted on the jaws of a vice. The algorithm examines all possible combinations of peg locations that come into contact with each set of edge segments, and then verifies force closure or the capability to resist arbitrary forces and torques.

The algorithm developed by Wallack and Canny [4] was extended by Brown and Brost [5] to develop a three dimensional (3-d) modular gripper. A 3-d, grasp quality metric based on force information, loading analysis, and inter-gripper interference was added to the planar algorithm.

Wu, Rong, Ma, and LeClair [6 – 7] proposed several modifications to Brost and Goldberg's algorithm[2]. These modifications are: alowing curved surfaces, allowing the use of locators other than circular locators, extending to 3-d fixture design, additional criteria for locating and clamping design, and incorporating frictional forces.

Ponce [8] proposed an immobilizing fixture for 3-d polyhedral parts. The proposed methodology uses four spherical locators to restrain the part. This method is a generalization of Wallack and Canny's algorithm[4].

Trappey and Matrubhutam [9] used projective geometry to simplify the complex 3-d problem to a simpler 2-d problem. Locating and clamping points were positioned on the projected envelope of the part and selected points formed the vertices of triangle with largest included area.

Roy and Sun [10] developed a prototype automatic fixture design system as a subsystem of a computer integrated manufacturing environment. They used the 3-2-1 locating principle. Later, Roy and Liao [11] proposed the use of geometric reasoning to enhance the locating positions proposed in the original work. The enhancements are based on a workpiece's deformation and tool interference.

Willy, Sadler, and Schraft [12] developed an automated process for fixture design based on specified machining forces and the resulting stability of the determined solution. Different clamping planes were determined from the part geometry. Different combinations of clamps were applied to the clamping planes. The stability and reaction forces were then used to select the optimal solution.

Lin, Zhang, and Nee [13] developed an integrated system for setup planning and fixture design. Their system identified feasible locating and clamping and then generated fixture configurations for each stage of the manufacturing process of the part. The fixture configuration was based on the part geometry, stability, modular fixture elements and interference.

Ma, Li, and Rong [14] developed an automatic fixture planning system based on the 3-2-1 locating principle. The fixture planning system automatically selected modular fixture components and then placed them in a final configuration in order to locate and restrain the workpiece.

Tao, Kumar and Nee [15] developed a method for determining the optimum clamping locations for an arbitrarily shaped part with a given set of locators. Feasible clamping locations were identified by calculating the convex hull of bounding wrenches, associated with constraining contacts, and determining if the convex hull contained the origin. The optimal solution was calculated based on the largest radius of the maximal inscribed hypersphere centred on the origin within the convex hull.

Hou and Trappey [16] examined the application of V-blocks to non-prismatic parts. An algorithm was developed to determine the location of the V-block and the corresponding horizontal clamp.

Tseng [17] developed a process to determine fixture configurations for prismatic parts with prismatic features during intermediate steps of manufacturing a part. In sequential operations, the workpiece geometry and fixturing constraints change so that the fixture configuration may need to be changed for subsequent operations.

Research has also been undertaken to incorporate artificial intelligence into computer aided fixture design. Lin and Yang [18] developed an expert system for a modular fixture. Their method determined the clamping positions based on the kinematic constraints as well as the clamping and cutting forces. The system also provided a learning concept to incorporate the knowledge gained from experience and also heuristic rules to enable repeated self-learning of possible clamp locations.

Sun and Chen [19] developed a modular fixture design system, based on case based reasoning. Knowledge in case based reasoning systems is stored as a problem and a solution to that problem. A new problem is solved by adapting a previous case to fit the new conditions. Then this new solution is stored and used to expand the knowledge of the system.

Wu and Chan [20] have applied a genetic algorithm to the problem of fixture configuration. The surface of the part is discretized and the locations of six locators and three clamps make up the genetic code. The genetic algorithm approach determines the most statically stable fixture configuration among a large number of candidates.

Lin and Huang [21] applied neural networks to the fixture planning problem. Group technology is used to identify fixture modes for different workpieces. The pattern recognition capability of the neural network allows it to identify the fixture mode of the workpiece.

Kumar, Subramaniam and Seow [22] applied genetic algorithms in the conceptual design of fixtures. A neural network, trained with a set of design samples, evaluates the fitness of proposed solutions. The genetic algorithm then allows the system to search a very large solution space and provide an optimal solution and a group of suboptimal solutions.

2.2 Fixture Hardware Design

The previously discussed research focused on the determination of fixture configurations based on modular fixtures. Research has also taken place in automating fixtures. Shirinzadeh [23][24] and Shirinzadeh and Tie [25] have developed a modular, reconfigurable system. The system uses a robot to assemble the desired fixture configuration based on information from a CAD database.

Kurz, Craig, Wolf, and Stolfi [26] developed a computer controlled high precision positioning mechanism. The device consists of two hydraulic cylinders that are connected and a reference base with a revolute joint. The device has two degrees of planar freedom with a positioning accuracy less than 0.001 inches.

Benhabib, Chan, and Dai [27] developed a modular programmable fixturing system. Their system incorporates sensors into the design so that the system can be automated for robotic assembly.

Chan and Lin [28] developed a standard multifinger module. The module consists of four fingers with eight degrees of freedom to conform to any arbitrary workpiece surface.

Du and Lin [29] developed an automated flexible fixture for planar objects. Their device consists of three fingers which restrain the part based on the largest inscribed circle within a polygon. Du, Lin, Zhao and Gol [30] added adaptive clamping forces to the flexible fixture. The system detects changes in a part's stiffness during machining to determine if the clamping forces should be reduced to prevent the part's further deformation.

2.3 Summary

Several conclusions can be drawn from the literature. Research has focused on developing the mechanical design of fixtures that are neither universally nor generically applicable. Algorithms for determining clamping and locating positions have been developed. The application of an engineering analysis that takes into account machining and clamping forces, workpiece deformation, accuracy and other factors has been done. However, none of the research benefits from the direct application of CAD (Computer Aided Design) data (ie the NC code) in determining clamping locations. Another topic that has not been considered is the repositioning of clamps, under computer control, to allow uninterrupted machining.

Chapter 3 Analysis

Metal cutting operations on milling machines traditionally employ a dedicated fixture that is specific to the part being machined. The milling process is analysed for each part type and the sequence of operations relies on the experience and knowledge of the operator. The operator positions the part, performs an operation, and reconfigures the fixture for the next operation. The process of reconfiguring the fixture for the next operation continues until all the required milling operations are complete. A few illustrative examples are examined below to demonstrate the difficulty of clamping a part. Figure 3.1 illustrates a rectangular part that needs machining on the inside of the part (pocket milling) as well as contour milling around the part's periphery.

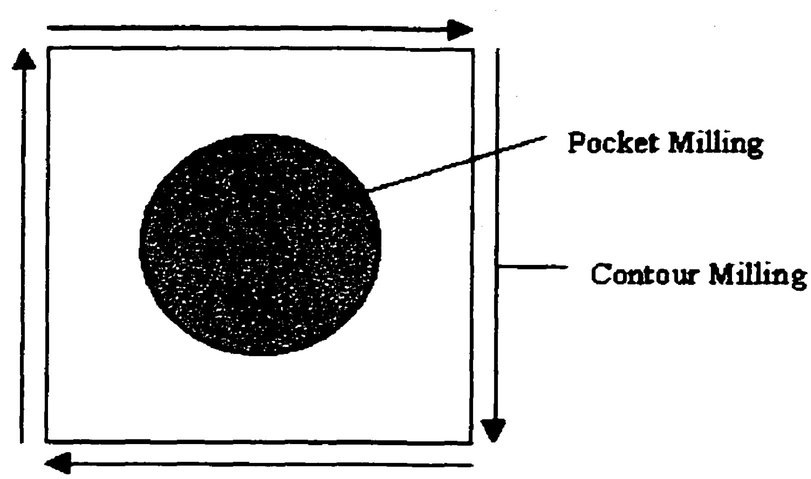

Figure 3.1 Rectangular part needing pocket milling

The part has flat surfaces on the top and sides so that standard clamps with flat gripping surfaces may be utilized. The part can be machined in two stages. First, the pocket milling is undertaken by holding the part from the side, as shown in Figure 3.2a. Then the contouring around the part can be completed using clamps holding the part as shown in Figure 3.2b. It should be noted that, for contouring around the edges, not all four clamps can be present at all times. One can start machining with all four being in place and remove one clamp at a time. As the tool traverses around the periphery, the clamp closest to the tool will be removed for a short time and repositioned as soon as the tool moves to a collision free zone.

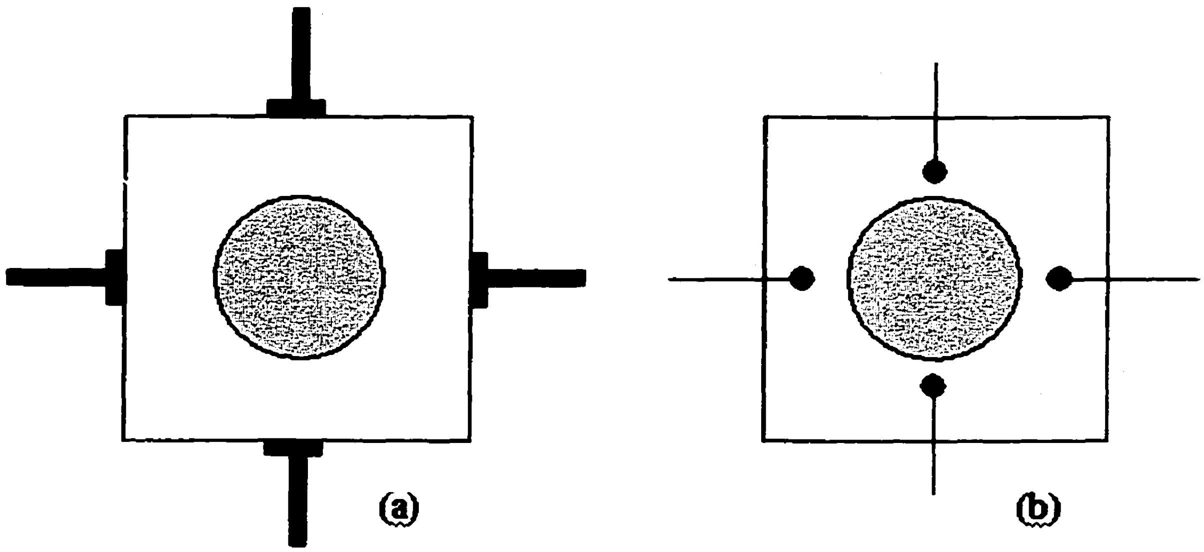

Figure 3.2 Clamping during pocket and contour milling

A simple triangle is considered as the second example. Possible configurations for holding a triangular part are shown in Figure 3.3. Figure 3.3a illustrates the use of three clamps located at the midpoint of each side of the triangle. In Figure 3.3b, conversely, v-blocks are utilized on the vertices of the triangle in order to restrain the part. Figure 3.3c demonstrates a strategy using a clamp and a v-block (custom developed for this case). When holding the part from the side, the clamps should exert a force that passes through the centre of the part to reduce the moment exerted on the part in the clamping plane. The sides of the triangular part, although flat, are not perpendicular which increases the complexity of positioning a clamp. It should also be noted that a contouring operation will require a reconfiguring of the clamps in order to access all the sides.

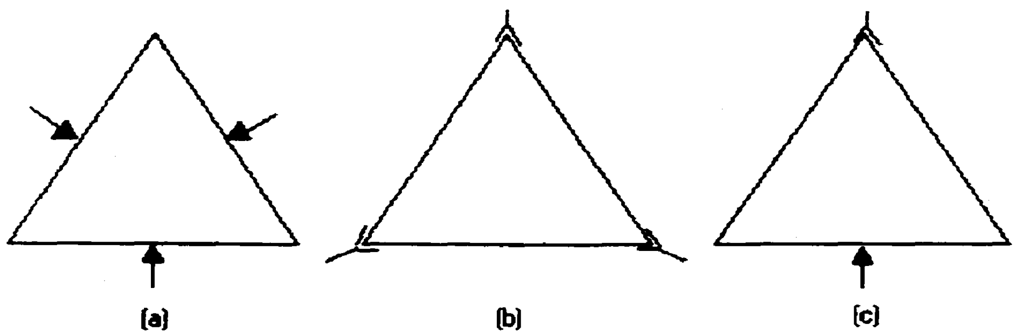

Figure 3.3 Methods of clamping a triangluar part

Different part geometries can be analyzed to arrive at an appropriate clamping configuration that securely holds the part. Consider the case where an operation is required on the outer boundary on which the part is to be held. The clamps must be reconfigured in order to avoid a collision with the tool. For example, if a contouring operation is required on the outer boundary of a triangular shape, the clamping configurations shown in Figures 3.2 and 3.3 will not permit milling of the contour using one clamp setting.

To machine the outer contour of a part, milling must be interrupted often to reconfigure the clamps. In addition, the part may also be disturbed during the process of reconfiguring the clamps. Interrupting the milling to reconfigure the clamps increases the time required to produce a part. Therefore, a fixture that has the ability to be reconfigured automatically is very desirable. The ideal situation would be a fixture that has the ability to be reconfigured dynamically without having to interrupt the operation of the machine. It would also be desirable to have all the operation fully automated using computer control. The example shown in Figure 3.4 illustrates a part that contains internal features which need pocket milling followed by a contouring operation around the outside to separate the part from the initial blank. The shaded regions in Figure 3.4 indicate areas that are pocket milled. The solid curve represents the outer boundary corresponding to a contour operation.

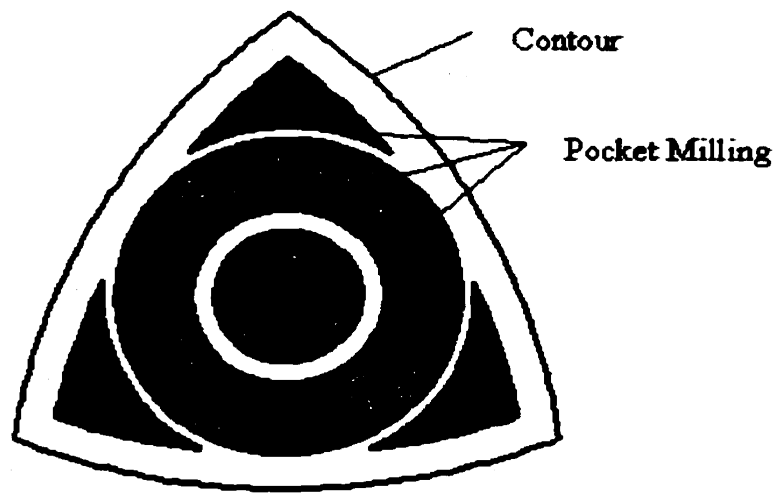

Figure 3.4 Part with internal details

The example shown in Figure 3.4 would ideally be held around the outside at the start of the operation to mill the internal features. When internal milling is completed, the clamping configuration would be changed to appropriate locations on the inside of the part in order to mill the outer contour. It would be preferable to perform this reconfiguration without manual intervention. During the repositioning phase, however, the part must be held securely. From an examination of this milling example, it can be concluded that the part must normally be held with more than the minimum number of clamps typically used for conventional machining. A redundant clamp would allow repositioning of any one of the clamps during operation and it would act as a backup to maintain stable holding of the part whenever stability becomes an issue.

The solution that this research proposes utilizes four independent top clamps to dynamically hold a part during machining. The fixturing system also incorporates a two stage milling process. In the first stage, the part is held at the outside edge of a blank work piece. In the second stage, the part is held at calculated clamping locations within the part. If, during the second stage, a clamping arm interferes with the path of the tool, the arm is removed momentarily. When the clamp no longer interferes with the milling operation, the clamp returns immediately to the previous clamping location. The clamping locations are calculated by employing the part's geometry and tool path information. More details are provided in the following sections.

The development of the clamping system is based on the main assumption that three top clamps are sufficient to hold a part during milling. The implication of this assumption is that there is a large frictional force between the workpiece, clamps, and the base that is sufficient to securely hold the part during machining.

Chapter 4 Methodology

4.1 Introduction

This section describes the physical system and the software algorithms used to simulate an automated fixturing system. A schematic of the system's configuration is shown in Figure 4.1. The system is broken into two main components: the clamping system and the milling machine within which the clamping system is located. One computer (Computer 1) controls the clamping system, a second computer (Computer 2) controls the milling machine. The control of the system could be integrated into one computer. On the other hand, the use of two computers provides a closer analogy of interfacing the clamping system with a stand alone machine controller. The proposed clamping system has four identical clamps, each having two degrees of freedom (d-o-f) for positioning the end point of each clamp. The operation of the two computers is co-ordinated by passing information across a parallel port cable that links the two computers. The operation of the fixturing system is coordinated by Computer 1. The operator loads a part geometry and NC toolpath information into Computer 1. Then the operator ensures that the fixturing system is configured and calibrated properly so that operations can begin. The next section outlines the part information used by the automatic clamping system, and describes the required hardware and software.

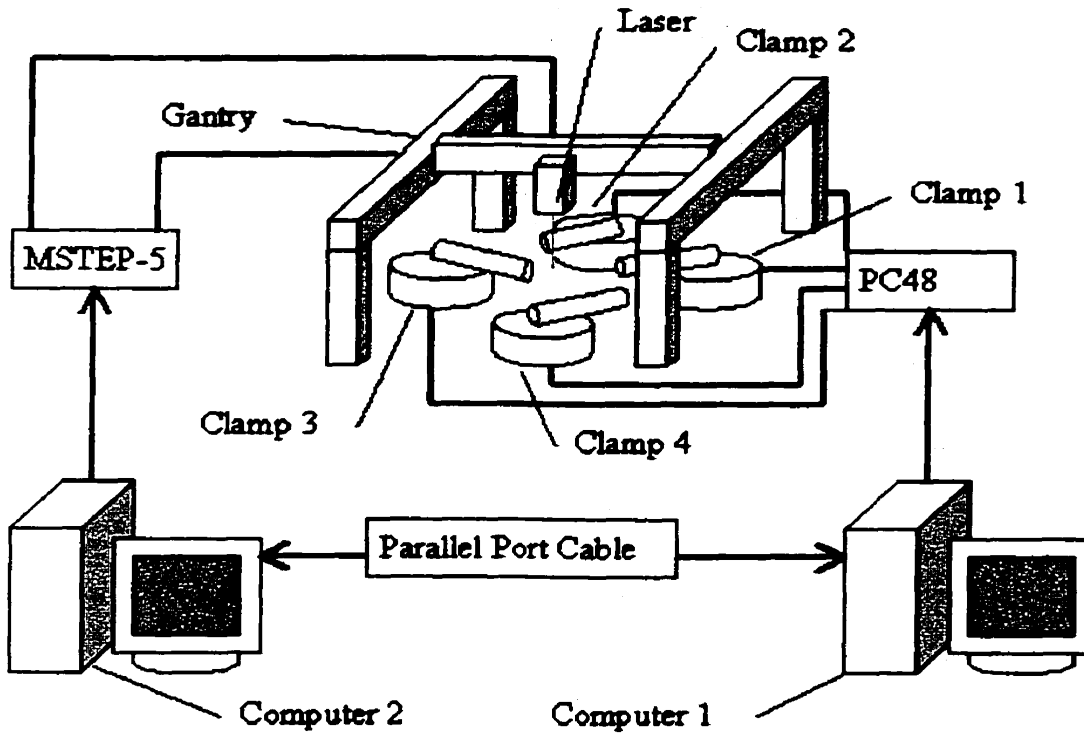

Figure 4.1 System configuration

4.2 The Part

The clamping system requires two sources of information: the part's geometry and the machining tool-paths. The part geometry defines the dimensions and entities while the tool-paths define how the part is machined. Commercially available, CAD/CAM packages allow the user to create the part geometry and the associated manufacturing process information. For this project, the geometry is restricted to 2 ½ dimensional planar parts created by using a three axis, CNC milling machine. A 2 ½ dimensional part implies that interpolations are made only in one plane but at different depths. The entities that make up the part are lines and arcs. Support for splines, surfaces, and other complex geometric entities can be added in the future.

The geometry information is created in a commonly used, commercially available CAD/CAM package Mastercam. The data files are proprietary and are readable only by employing Mastercam. However, all CAD systems provide information on a part's geometry in a neutral file format. In order to ensure that the clamping system will work with any other CAD system, a neutral file format is used here. The Initial Graphics Exchange Standard (IGES) file format is one such neutral file format for facilitating the exchange of graphical information between CAD systems. The structure and details of the IGES file format is discussed in greater detail in section 4.3.2. The IGES format supports all geometric entities.

Tool-paths are created in Mastercam, based on a user's inputs. The user selects the type of operation, the geometry for defining the operation, the tool, the depth of cut, and options that affect the behaviour of the tool. Mastercam uses a post processor to convert the tool-paths into a numerical control (NC) code, which is specific to the milling machine used. The NC code follows the standard word address format.

4.3 Clamping

4.3.1 Hardware

The clamping system has four independent top clamps with a clamping area of $20mm^2$ for each clamp. The clamping area is chosen arbitrarily and it can be reduced or increased to almost any size by an appropriate choice of the clamping pads. However, the clamping algorithm must be provided with this information. Each arm has a radial and an angular degree of freedom (d-o-f) for a total of eight degrees of freedom. The configuration of a top clamp is shown in Figure 4.2. The radial d-o-f utilises a lead screw to radially move a clamp's arm assembly. The motion of the lead screw is controlled by employing a computer controlled, stepper motor. The angular degree of freedom is created by using a rotary table. The rotary table is controlled by utilizing a stepper motor, belt drive system.

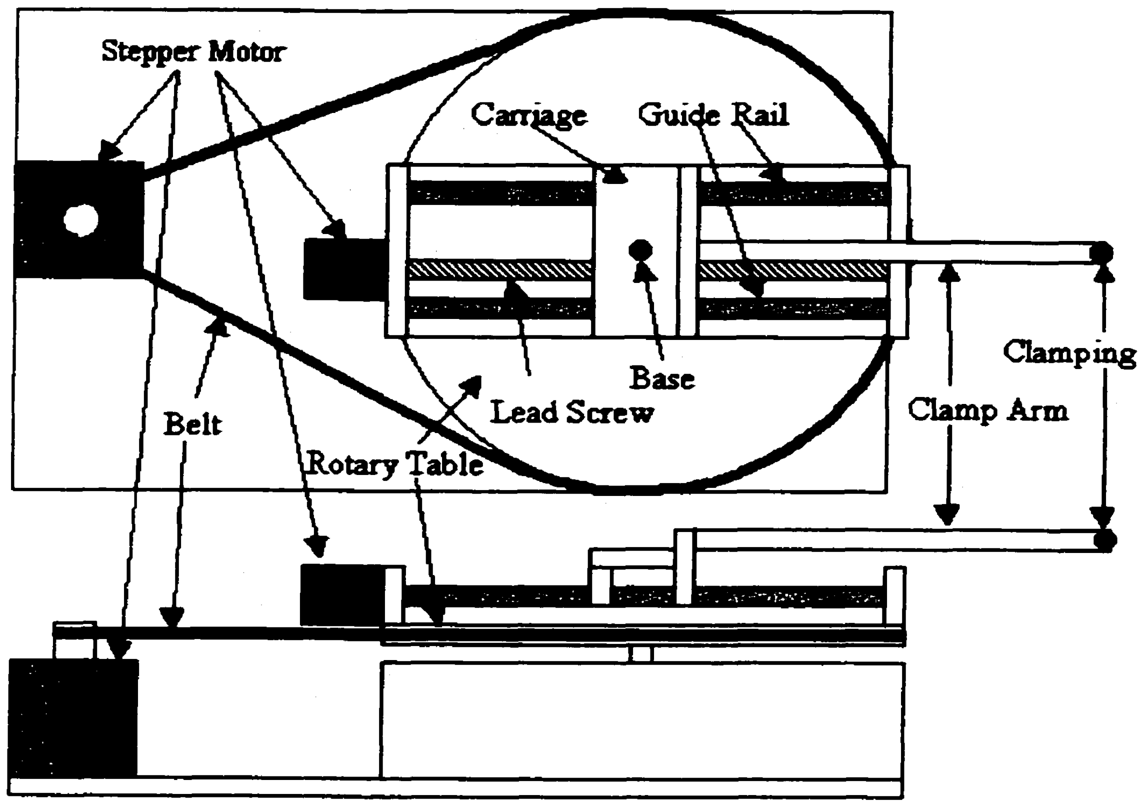

Figure 4.2 Top clamp configuration. Not to scale

The stepper motors are controlled using an Oregon Micro Systems PC48 stepper motor controller card. This card is capable of simultaneously controlling eight separate stepper motors. The stepper motors are labelled R, S, T, U, V, X, Y, and Z in Figure 4.3. For example, it can be seen from Figure 4.3, that stepper motor R corresponds to the angular d-o-f of Clamp 1 and motor S corresponds to the radial d-o-f of Clamp 1. Each stepper motor is interfaced with the controller circuit that is shown in Appendix B. Since the purpose of this work is to demonstrate the feasibility of the methodology, it was decided to use existing resources in the laboratory. Stepper motors are relatively simple to control and are accurate provided they truly respond to the command pulses. A servo driven system would be the other option for driving the fixturing system. A servo driven system requires feedback to control the angular positioning and it is more expensive and complex to control. In the design proposed, the drive motors carry minimal load and do not need large torque or position feedback; hence the choice of stepper motors for the drive system.

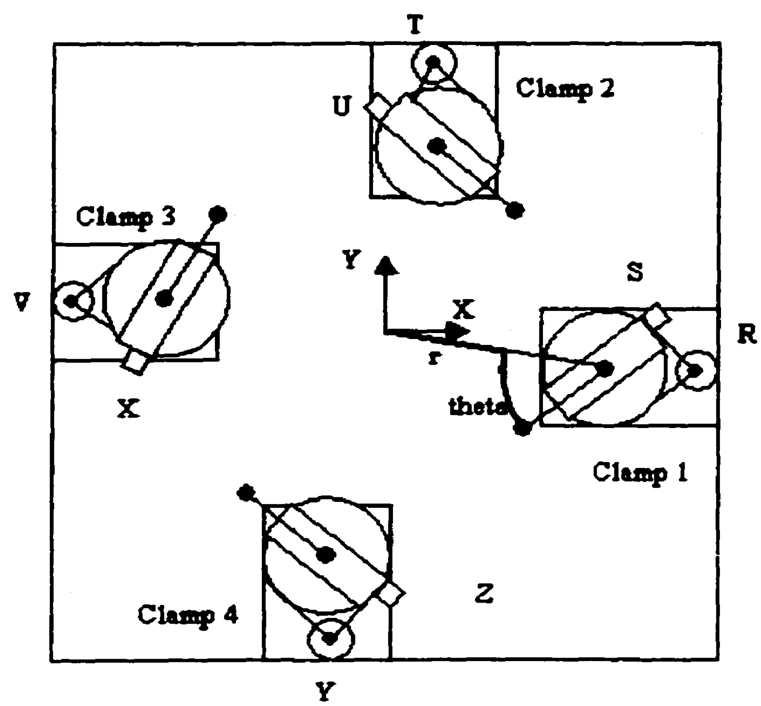

Figure 4.3 Configuration of clamping system. Not to scale

All the clamps are located within the reachable envelope of the milling machine. The clamping system is shown in the zero or home position in Figure 4.3. Table 4.1 gives the co-ordinates of the base (centre of rotation of the clamp) and the end of the clamp arm in its home position. The co-ordinates given in Table 4.1 are with respect to the co-ordinate system shown in the centre of Figure 4.3.

Clamp	Base		Home	
	x (mm)	y (mm)	x (mm)	y (mm)
1	227.3	28.7	119.4	-69.4
2	-30.5	224.5	68.6	121.1
3	-232.9	-26.3	-124.5	69.6
4	31.2	-224.6	-78.7	-116.4

Table 4.1 Clamp locations

The resolution of the clamps is calculated from the number of steps required for each clamp to move from the home position to the mill's zero position. The angle of rotation (theta) and radial extension (r) can be calculated from the home, base and zero positions shown in Figure 4.3. The steps per millimetre and steps per radian are calculated for each axis. They are shown in Table 4.2.

Clamp	Angular Degree of Freedom				Radial Degree of Freedom			
	Axis	theta	Steps	Step/rad	Axis	r	steps	Step/mm
1	R	-0.61	-180	294.	S	83.3	-13100	-157.
2	T	-0.63	184	-292.	U	83.4	13000	155.
3	V	-0.61	-183	299.	X	89.6	-13900	-155.
4	Y	-0.66	185	-282.	Z	72.4	11000	152.

Table 4.2 Clamping axis parameters

The PC48 stepper motor controller card controls a clamp's end position. An internal register in the PC48 card monitors the position of each axis. The home position is defined as the zero for each axis. Therefore, movement to different locations requires calculating the number of steps that the desired position is away from the home location. The PC48 card simultaneously controls each axis to move to the desired position.

4.3.2 Software

Clamping locations are determined by using the part's geometry and the NC tool-paths. This section outlines the algorithm used to identify the clamping locations. The clamping control program is written as a Windows based program that is compiled using Borland C++ 5.02 [31]. Geometric information is displayed in the main window by using the OpenGL libraries from Silicon Graphics and Microsoft[32]. The program also uses dynamic link libraries to access the PC48 stepper motor controller card and the parallel port [33].

The program reads the part geometry from the IGES file created by Mastercam. This file contains information about the entities that compose the part. An example of an IGES file is shown in Appendix A. The file is scanned initially to determine the total number of lines and arcs. The endpoints of each line segment, as well as the endpoints and centre point of each arc, are read from the data file.

Geometric information is used to determine appropriate clamping locations and intermediate positions that do not interfere with the milling operation. To accomplish this objective, the program uses common endpoints of lines and arcs in order to automatically chain the outer boundary of the part. An example is shown in Figure 4.4.

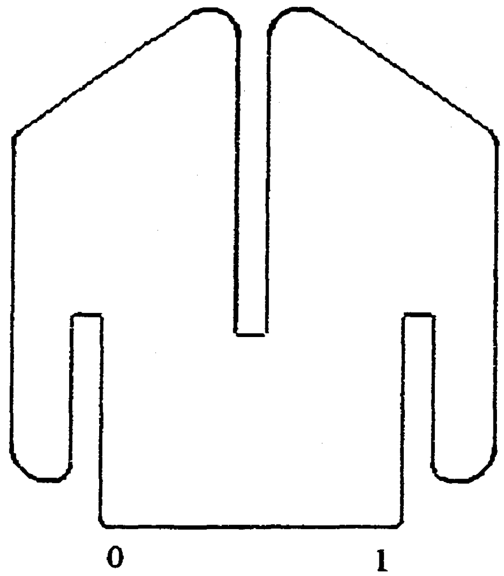

Figure 4.4 Finding the outer boundary

For the part shown in Figure 4.4, the outer boundary consists of a series of points that define connected line segments. The lowest entity (0-1 shown in Figure 4.4) is selected first with the starting point being point 0. Next, an entity with an endpoint that is common to point 1 is selected and the other extreme endpoint is labelled point 2. If there is more than one entity, the largest angle between the two vectors is selected. For an arc, intermediate points are added to maintain the desired profile by employing a series of linear approximations. Intermediate points on an arc are spaced 3.3° apart to approximate the curve, as shown in Figure 4.5. The process of selecting the next endpoint is repeated until point 0 is reached. The boundary defining the part must form a closed loop. If this requirement is violated, the geometry does not define an area and locations within the part cannot be calculated.

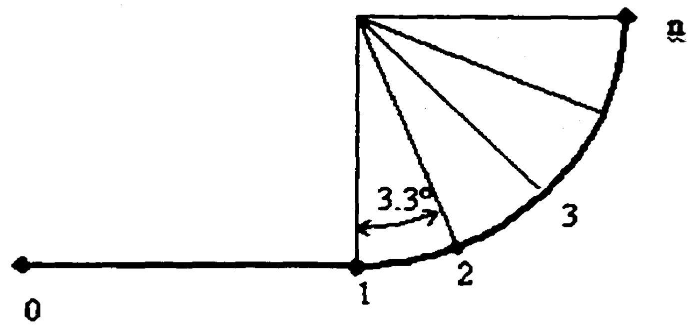

Figure 4.5 Circular interpolation of an outer boundary. Not to scale

Tool-path information is obtained from a specified NC file that is created by using Mastercam. The NC file contains the commands that control the milling machine during its operation. The code contains a sequence of positions for the cutting tool to follow by using either linear or circular interpolations. A sample NC file is given in Appendix C. Figure 4.6 shows the tool-paths associated with a contour around the outer boundary of the illustrated shape. The NC code can be considered a sequence of positions that define the path of the milling tool. The program extracts the start point, endpoint, type of interpolation (linear or circular), tool used, and the feed rate for each line of the NC code. The user has an option of performing single stage or two stage milling operations. Single stage milling requires one NC file that controls the tool during which the part is held within the part geometry. Two stage milling operations require two separate NC files. The first file corresponds to the initial milling operations while the fixture holds the part around the periphery of the blank workpiece. The second file corresponds to the final milling operation during which the part is held within the part's geometry. To calculate the clamping locations, the program combines the toolpaths of the two stage milling operations and treats them the same as in the single stage milling case.

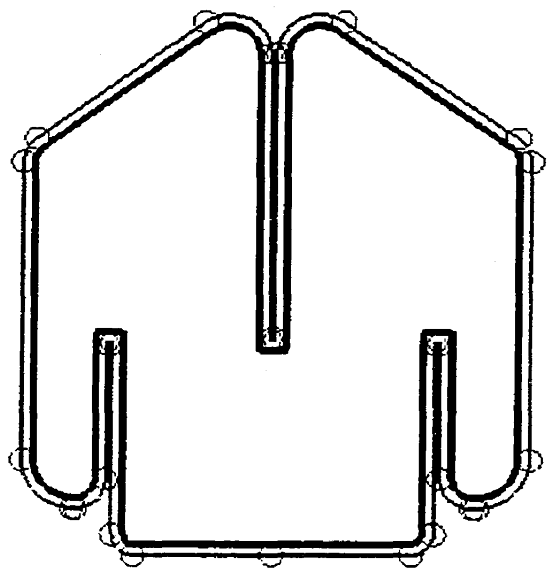

Figure 4.6 NC tool-paths

Consider the part shown in Figure 4.6. Machining required is to contour around the periphery of the part. For two stage milling, the clamping locations for the initial stage are located on the vertices of a bounding rectangle shown in Figure 4.7. To ensure that the clamp will not interfere with the milling tool, the sides of the rectangle are located in the extreme x and y directions plus the sum of the clamping pad's diameter and the largest tool diameter used to machine the part.

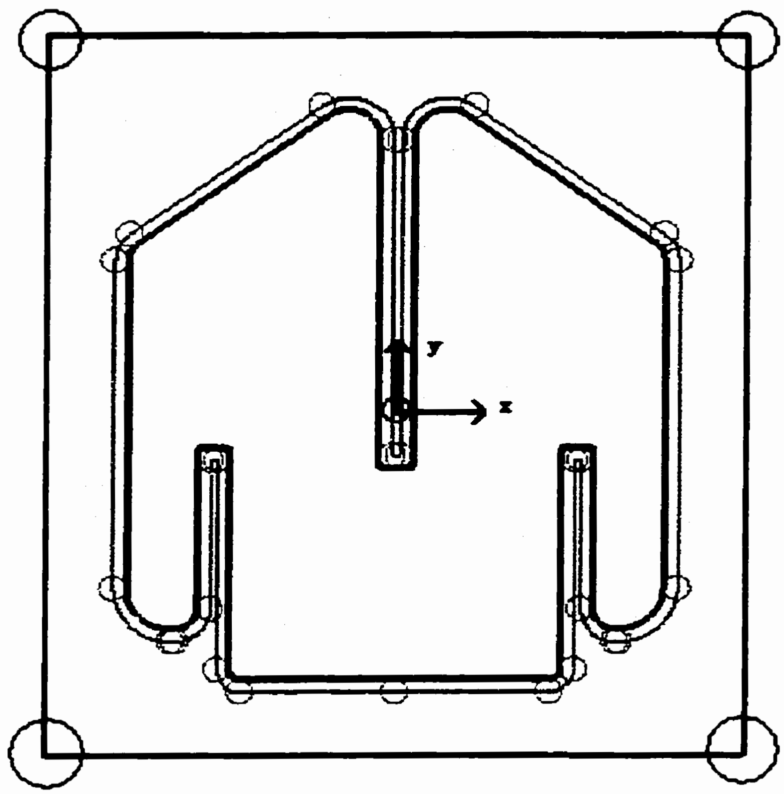

Figure 4.7 Rectangle defining the clamping locations for initial milling

The tool-paths and outer boundary of the part consist of a series of points. To quickly determine if a location is machined, an overlaying 0.5mm x 0.5mm grid, as shown in Figure 4.8, is created that encompasses the entire part. The grid size is chosen arbitrarily to meet the resolution required for the clamping area yet reduce the computational effort. To identify all the machined grid locations, the position of the milling tool is interpolated along the tool path with all grid points within the tool radius being marked as machined.

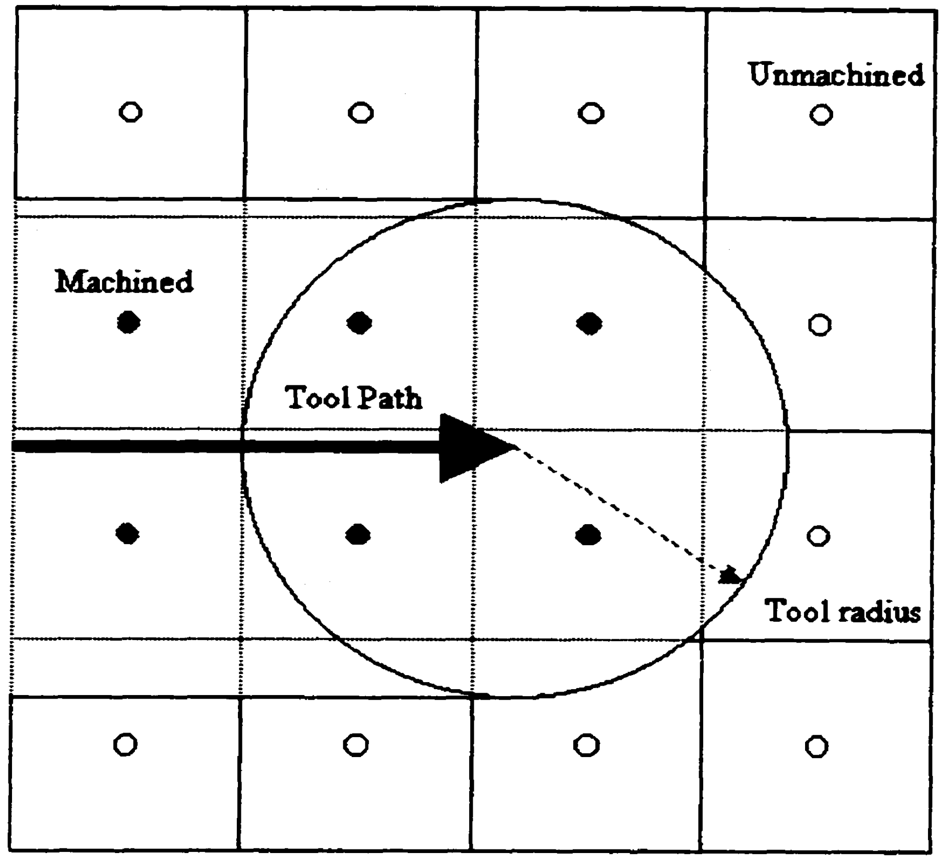

Figure 4.8 Grid and machined areas. Not to scale

After the machined areas have been determined, possible clamping locations are identified. The clamping locations must be located in unmachined areas within the outer boundary. Intuitively, the configuration of the clamps that will best overcome the forces generated during machining will be located around the periphery of the part. A larger clamping arm distance, with respect to the moment axis, will result in maximum reactive moments. Therefore, potential clamping locations are located a specified offset inside the outer boundary. This offset value is chosen somewhat arbitrarily to be two thirds the clamping location's diameter, or 5mm by default. Of the potential clamping locations that are identified, four are selected to hold the part. The algorithm initially displays all the locations that are approximately a clamping diameter apart. Then each potential clamping location is checked to ensure it is located in an unmachined area within the part's geometry. The potential clamping locations for the given example are shown in Figure 4.9. This method provides a number of potential clamping locations whose number is proportional to the length of the perimeter of the outer boundary.

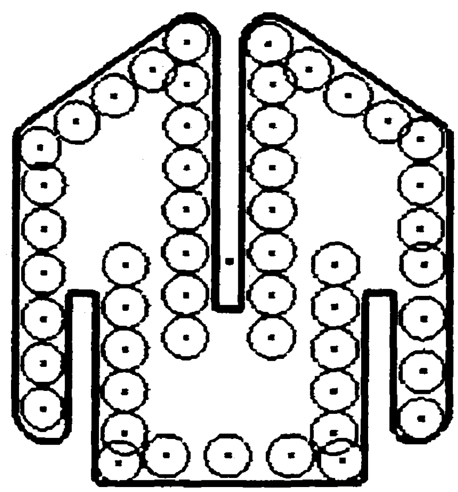

Figure 4.9 Potential clamping locations

Once the possible clamping locations are found, four locations are selected to hold the part. The strategy to select the clamping locations (explained on the next page) gives a score to each possible combination of four points. The combination with the highest score is selected. A possible combination of clamping locations is shown in Figure 4.10.

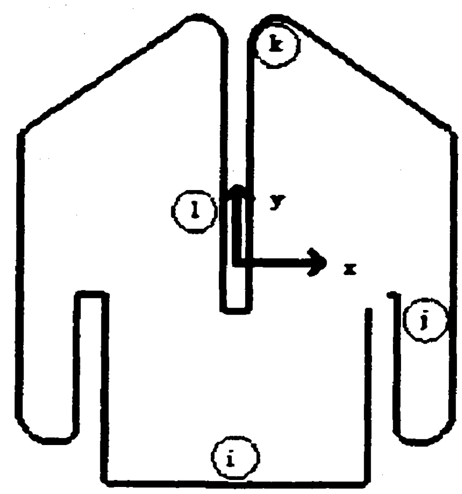

Figure 4.10 Possible combination of clamping locations

The score is composed of the sum of three components. These components are the total of the distances between the individual clamps, the moment applied to the part assuming the part is rigid with equal clamping forces, and the distance between the clamps and the centroid of the part. The combination of points with the maximum score are selected as the clamping locations for holding the part. Typical clamping locations are shown in Figure 4.10. They are labelled i, j, k, and l. The score for a typical set is given by

$$score = \frac{D(i,j,k,l)}{Max(D)} + \frac{Min(M_{xy})}{M_{xy}(i,j,k,l)} + \frac{M_z(i,j,k,l)}{Max(M_z)}, \tag{4.1}$$

where D is the sum of all distances between each possible clamping location. It is defined as

$$D(i,j,k,l) = \left|\overline{ij}\right| + \left|\overline{ik}\right| + \left|\overline{il}\right| + \left|\overline{jk}\right| + \left|\overline{jl}\right| + \left|\overline{kl}\right|. \tag{4.2}$$

Max(D) is the maximum value of D(i,j,k,l) for all possible combinations of clamping locations. M_{xy} is the resultant moment of the clamping forces about the x and y axis and is given by

$$M_{xy}(i,j,k,l) = Max\left\{\begin{array}{l} \left|\overline{r_i} \times \overline{F_i} + \overline{r_j} \times \overline{F_j} + \overline{r_k} \times \overline{F_k}\right| \\ \left|\overline{r_i} \times \overline{F_i} + \overline{r_j} \times \overline{F_j} + \overline{r_l} \times \overline{F_l}\right| \\ \left|\overline{r_i} \times \overline{F_i} + \overline{r_k} \times \overline{F_k} + \overline{r_l} \times \overline{F_l}\right| \\ \left|\overline{r_j} \times \overline{F_j} + \overline{r_k} \times \overline{F_k} + \overline{r_l} \times \overline{F_l}\right| \end{array}\right\} \tag{4.3}$$

Min(M_{xy}) is the minimum of M_{xy}(i,j,k,l) for all possible combinations of clamping locations. M_z is the moment of the friction forces about the z axis. It is given by

$$M_z(i,j,k,l) = \mu \cdot F \cdot \left(\left|\overline{r_i}\right| + \left|\overline{r_j}\right| + \left|\overline{r_k}\right| + \left|\overline{r_l}\right|\right) \tag{4.4}$$

Max(M_z) is the maximum of M_z(i,j,k,l) for all possible combinations of clamping locations.

A clamp must be assigned to each clamping location. The intention of the algorithm is to assign all the clamps to locations that minimize the overall distance between each clamp base and its location. The distance between a clamp base and a clamping location is given by δ_i as shown in Figure 4.11. Minimizing the sum of all δ_i ensures that the clamps do not interfere with each other as they are repositioned. The sum of clamp arm lengths is calculated for all possible combinations. The configuration that has the minimum total clamp arm length is then selected. It is shown in Figure 4.11 for the particular example shown in Figure 4.10.

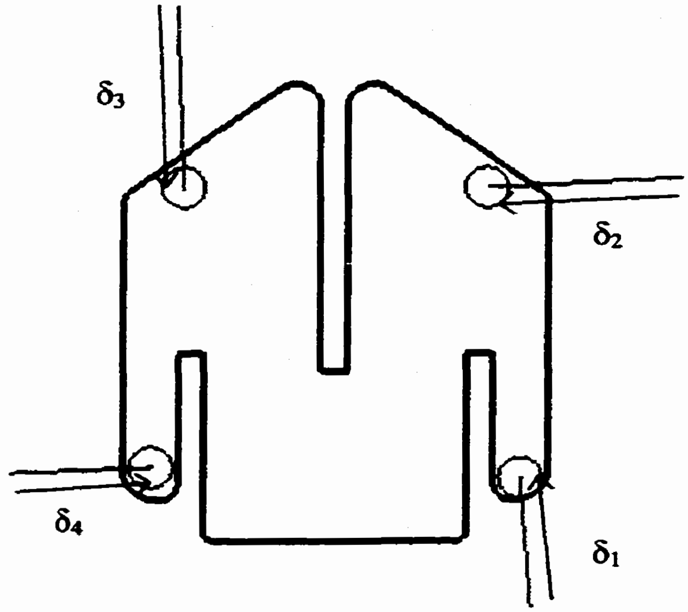

Figure 4.11 Assigning clamps to locations

An intermediate position is determined for a clamp to move to if the clamp shows a potential collision with the milling tool. This position is located radially outward through the clamping location from the centroid of the part. The position is located the maximum tool diameter plus the diameter of the top clamp from the edge of the part to ensure that the clamp does not interfere with an external contouring operation. The clamping configuration and the moves needed to avoid a collision are shown in Figure 4.12.

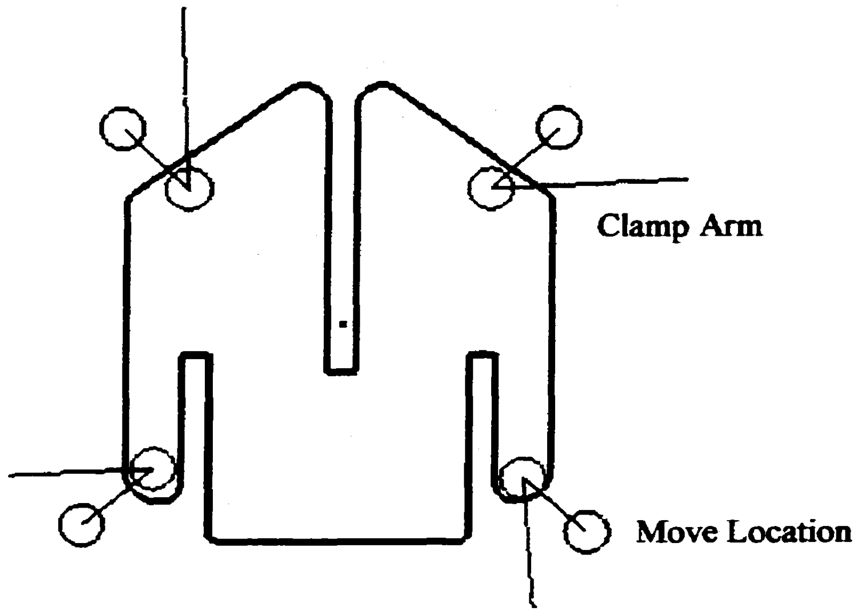

Figure 4.12 Clamping arm locations and clamp moves

The clamping system is ready now to interact with the milling machine. The operation of the clamping system is described in Section 5. The next section outlines the components and algorithms developed to simulate the operation of a milling machine.

4.4 Milling

4.4.1 Hardware

A standard milling machine is capable of co-ordinated movements along three independent axes. For the purposes of this research, a two axis overhead gantry system, that is controlled by a Metrabyte MSTEP-5 motion control board [34], is used to simulate a milling machine. The mill head does not move in the vertical direction as would be the case in a real mill. However, for the purpose of demonstration this vertical motion is assumed to be present. The system is capable of a maximum feed rate of 500 mm/min. The position of the cutting tool is displayed by a focused spot generated by a laser interferometer. The laser merely provides a visual representation of where the tool is to be located. Any likely interference with the clamping system can be seen visually.

4.4.2 Software

The control software for the milling machine is written in C++ as a DOS application compiled with Borland C++ 5.02. It allows the user to independently control the milling machine or let the mill act in concert with the clamping system. This section outlines the basic functions of the control software and the algorithms used to control the motion of the milling machine.

The software controls the gantry system so that the laser follows the defined tool-paths given in the NC code. The NC code is a series of instructions that control the behaviour of the milling machine. The motion of the tool head is specified by linear and circular interpolations between different positions. The NC code also contains information about the feed rates, tool changes, and as well as the commands to turn the spindle on and off.

Linear interpolations are specified by standard NC codes. For example, a G0 code specifies a rapid traverse to the next position without regard to the path taken. A G1 code specifies the tool to move to a given location by using linear interpolation from the current position. This system treats G0 and G1 codes identically in comparison to a standard CNC system. The software calculates the number of steps between the current position and the next position and the time required for the movement based on the specified feedrate. Then the software checks to ensure that the system is capable of the required speed for each axis and, if necessary, increases the required time until the feedrate is possible. The maximum stepping speed that the stepper motors permit is 328 pulses/s. The maximum stepping rate and the resolution of the gantry (0.0254mm) corresponds to a 500mm/min feedrate. The stepping speed is determined from

$$PPS = \frac{100000}{(FD+1)\times RA}. \tag{4.1}$$

This equation is specific to the hardware used and it is obtained from the M-STEP5 manual. The frequency of the internal clock used by the card to drive the stepping motor pulses is 10000Hz. To determine the stepping speed, the driving frequency is divided by the 8bit values, FD and RA. FD, which is called the frequency divider, takes an integer value between 1 to 255. RA, the clock divider, is an integer value between 20 and 255. The values of FD and RA are calculated to give the closest stepping speed available to the desired stepping speed for the x and y axes of the milling machine.

Clockwise interpolations are specified by a G2 command while counter-clockwise interpolations are specified by a G3 command. An arc is split into 0.05 radian increments with the position of the mill specified at each increment. In this manner, circular interpolations are approximated by a series of linear interpolations.

During machining, the software determines if the clamp arms interfere with the motion of the cutting tool. The mill does not have encoder feedback and, hence, the exact position of the milling tool is determined at any instant by using software tools. The position is monitored using a software interrupt. The interrupt is tied to the computer's internal timer which operates at 18.2Hz. During each interrupt, the position of the milling tool is updated and the perpendicular distances between the tool and each of the clamps are calculated. If the distance between any one of the clamp arms is less than a specified distance, that clamp arm is considered to be interfering with the tool. The default threshold distance used in the simulation is 10mm. When a clamping arm interferes, the milling machine sends a signal to the clamping system that indicates which clamp arm is determined to be interfering. Details of the signal sent to the clamping machine are discussed in Section 5.1.

This section has described the operation of the individual components of the fixturing system. The determination of the clamping locations from the geometry and NC information has been examined in conjunction with the control software of the mill. In the next section the interaction of the two systems is outlined in order to illustrate how the fixturing system operates as a whole.

Chapter 5 Implementation

For successful operation, an automatic clamping system must have a means of co-ordinating the operation of the computer in control of the clamping system and the computer in control of the milling system. This section summarizes the reasons why two computers are used to control the system, the method used to transfer information between the two systems, as well as the operation of the clamping system itself. First, details of the parallel port cable through which the two computers are linked is described. Then the use of the cable to transfer the clamping locations and base location is detailed. Finally, the interaction during operations of the mill and clamping system is outlined.

5.1 Parallel Port Cable

The primary reason why two computers are used to control the automatic clamping system is to mimic the real-world situation of establishing a link between the CNC controller and the external interface computer. Commercial CNC controllers do not allow a control system to be modified. Even though an integrated system would be beneficial, it is realistic to separate the milling control and the clamping control. Communication between the two computers is achieved over a custom developed, parallel port cable. The parallel port has three port addresses or registers, namely the STATUS port, CONTROL port and DATA port. The STATUS port has four inputs and the CONTROL port has four outputs.

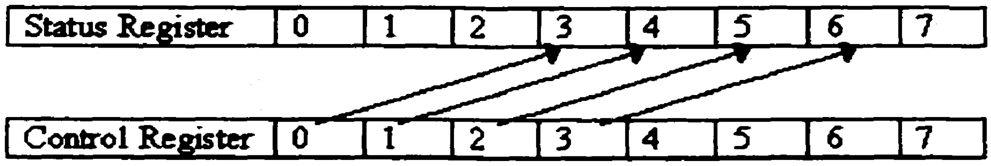

Figure 5.1 Status and control register bit assignment

The cable is wired such that the control register of each computer is connected to the status register of the other computer, as shown in Figure 5.1. With this connection, four bits of information that indicate the current status of the system and initiate different commands can be passed between the computers. The values and corresponding states are shown in Table 5.1.

Value	State or Command
0	Wait
1	Transfer Parameter File
2	Transfer Initial Milling NC File
3	Transfer Final Milling NC File
4	Start Initial Milling
5	Start Final Milling
6	Finished Initial Milling
7	Finished Initial Milling
8	Test Clamping Locations

Table 5.1 Bit values and associated modes

The DATA port is bi-directional. Bits are wired such that bit 0 corresponds directly to bit 0 and so on. This wiring of the DATA port allows information to be transferred one byte at a time. In order for the 8-bit DATA port to be bi-directional, the parallel port must be configured as an extended capability port (ECP) in the motherboard's BIOS. Bit 5 of the control register must be set high to allow the DATA port to accept inputs.

5.2 Clamping Location and NC File Transfer

After the clamping system has determined the clamping locations from the part's geometry and NC tool-paths, the user opens the Automatic Clamping System dialog box shown in Figure 5.2.

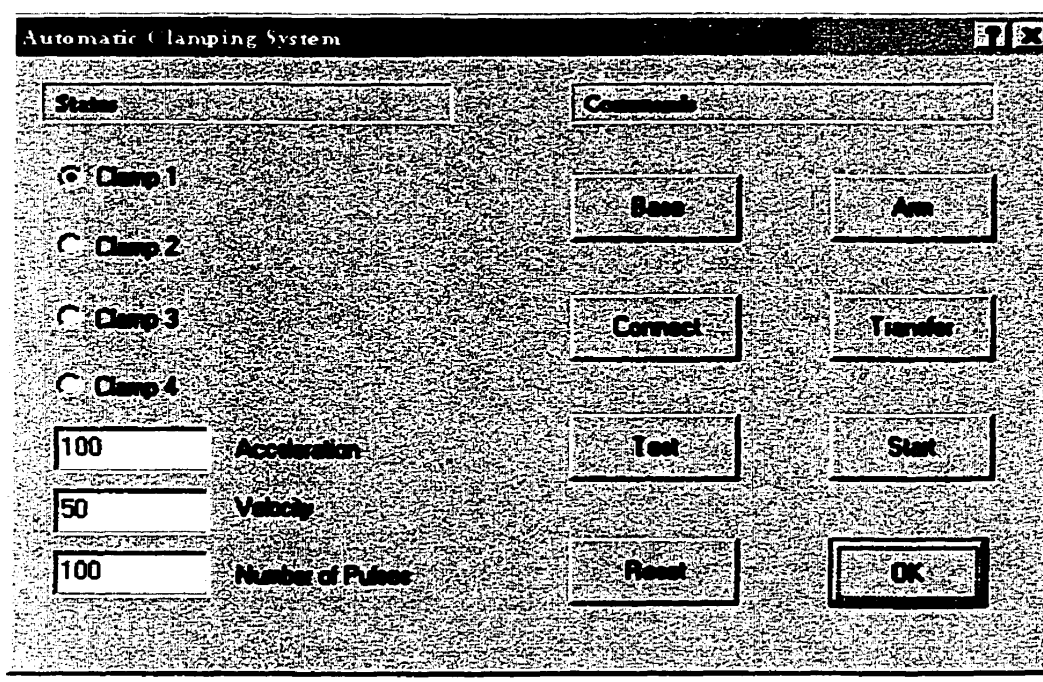

Figure 5.2 Automatic clamping system dialog box

This dialog box allows the user to interact with the clamping system. The command and status fields shown in Figure 5.2 display the commands, responses and status of the system. The Base button causes the base of the specified clamp to move the given number of steps at the specified speed (in steps/s) at the specified acceleration (steps/s^2).

The arm button has a similar effect as the base button, except it moves the arm rather than the base.

In order to communicate with the milling machine, a connection must be established across the custom built, parallel port cable. The connection can be initiated with the connect button. It is established by setting a bit in the control register of the clamping computer and checking if the milling computer responds by setting the appropriate bit. Once the connection is established, the clamping locations and NC program must be transferred from the clamping computer to the milling computer. The file transfer is initiated by pressing the transfer button shown in Figure 5.2. The clamping computer sets the command to transfer the parameter file. This file contains the clamping locations and indicates if the milling operation has one or two stages. The NC files are then transferred to the milling computer. The files are transferred, byte by byte, across the DATA register of the parallel port.

5.3 Operation during Milling

When the NC tool-paths have been transferred to the milling machine, the user can initiate the operation by pressing the start button. If the user has selected a two stage milling operation, the clamping computer moves the clamps to the initial milling clamping locations shown in Figure 4.7. Once the clamps are in position, the command to start the initial milling is sent to the milling machine. When the initial milling is complete, the clamps are moved, one by one, to the calculated final milling clamping locations shown in Figure 4.12. If two stage milling is not selected then the clamps move directly to the clamping locations shown in Figure 4.12. When the clamps arrive at the final milling location, the command to start final milling is sent to the milling machine. It is possible during final milling for the clamping arms to interfere with the milling tool. The milling machine calculates the distance between each of the clamping arms and the milling tool. Any clamping arm that is within a specified threshold distance of the milling tool is determined to be interfering. The number of this clamp arm is then placed in the DATA register of the parallel port. The clamping computer polls the DATA register of its parallel port during final milling. The value of the DATA register indicates which clamp is interfering. For example, if clamp 2 is interfering, then 2 is placed in the DATA register by the milling computer. The clamping computer reads this value and moves clamp 2 to the position shown in Figure 4.12. When clamp 2 no longer interferes with the milling tool, the milling computer places a zero value in the DATA register. The clamping computer detects this change in value and moves clamp 2 back to the original clamping location.

This section has detailed the operation of the fixturing system. Results will be examined in the next section to identify the key properties of this fixturing system and determine appropriate recommendations.

Chapter 6 Results and Recommendations

This section discusses the effectiveness of the automated clamping system in a simulated machining machining environment of parts with a wide variety of complexity. First the performance of the system during clamping a part is examined in more detail. Then other part configurations are considered to demonstrate the strengths and weaknesses of the system. Finally, recommendations to improve the system are discussed.

6.1 Operation of the Developed System

The performance of the fixturing system can be assessed by looking at the interaction of the clamping system with the milling system. The user has the option of specifying a two stage or single stage milling operation. The first stage of the two stage milling enables machining of internal details and contours around the outside of the part geometry. The blank workpiece must have adequate area to position clamps around the periphery of the part for a two stage milling operation.

The example workpiece shown in Figure 6.1 has to undergo a contouring operation around the outer boundary.

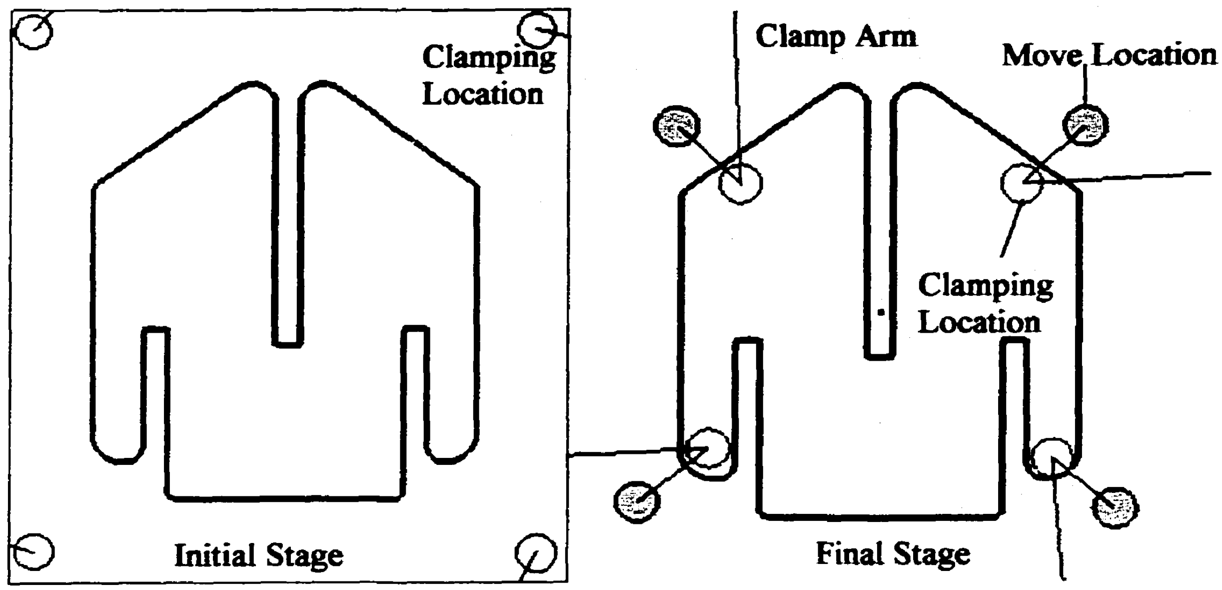

Figure 6.1 Initial and final clamping configurations

The final or single stage milling holds the part within the defined part geometry. It is possible for the clamp arms to interfere with the milling tool during final or single stage milling. When the distance between a clamp arm and the tool becomes less than a specified threshold value, that clamp arm is considered interfering with the mill. The area around a clamp arm is considered an interference zone. The interference zone for each of the clamps is shown in Figure 6.2.

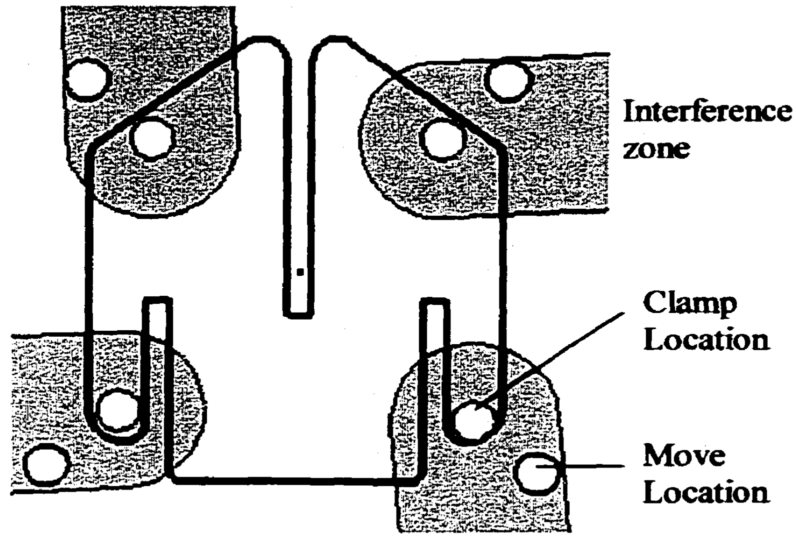

Figure 6.2 Interference Zones

When the milling tool is within an interference zone, the clamp moves to an intermediate position which will not interfere with the milling machine. The segments of the tool-path and the corresponding configuration of the clamping system during interference is shown in Figure 6.3 for the example considered.

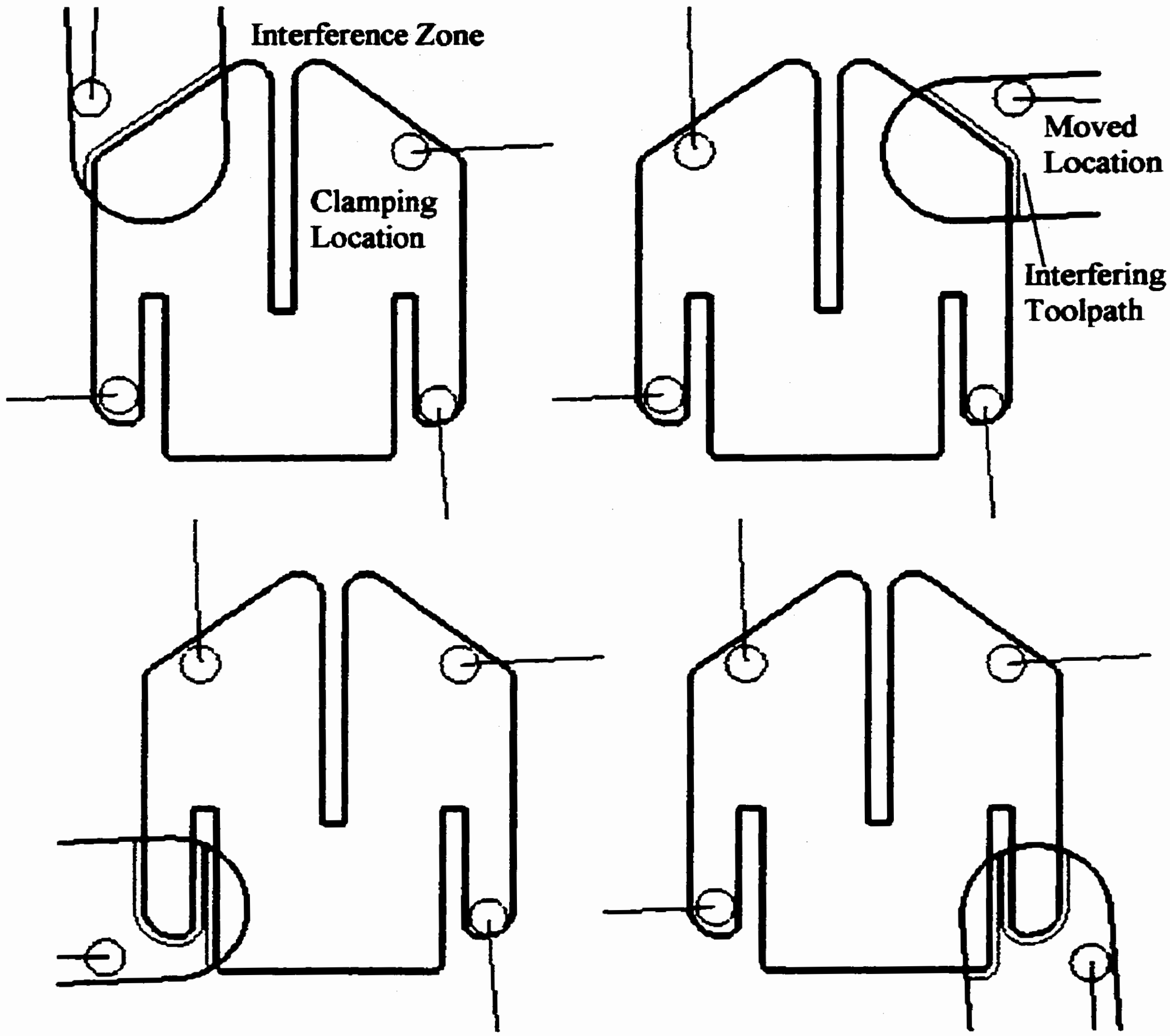

Figure 6.3 Clamping Configurations during Milling

The threshold value to determine interference must be large enough for the clamp arm to move clear before the tool enters the interference zone. The speed at which the clamp arm can move depends on the drive mechanism and stepping speed of the motor. The radial degree of freedom, controlled by a lead screw, is capable of moving at approximately 2mm/s. The radial motion is much slower than the angular motion of the clamp. The worst case scenario involves a primarily radial motion when moving the clamp arm to the clear position. For adequate performance, the radial speed of the clamp should be at least the same as the feed rate of the milling machine. Therefore, the speed at which a clamping arm can move limits the possible milling feedrates.

6.2 Results for Selected Example Parts

To illustrate the properties of the clamping system a variety of different parts are examined. Only the results for single stage or final stage milling are shown. The first example illustrates machining an outer contour around the irregularly shaped part shown in Figure 6.4. The outer boundary involves several arcs and contains flat boundaries. Hence, the part cannot be clamped from the side. The positions shown (labelled 1, 2, 3 and 4) are the four positions determined by the developed algorithm. Intermediate locations (1', 2', 3' and 4') to which the clamps will be positioned during potential collision with the tool as determined by the algorithm are also shown in Figure 6.4. The testing of the strategy verified that the determined positions produce collision free machining.

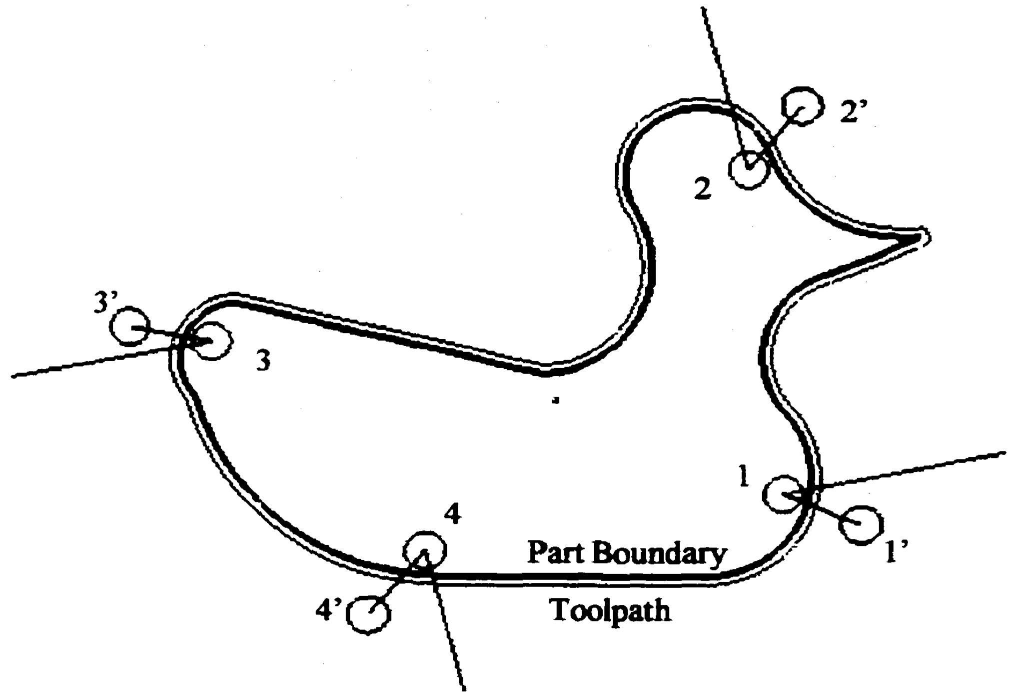

Figure 6.4 Outer contour of an irregularly shaped part

The second example illustrates milling of a circular part with internal details. A 3-d view of the part is shown in Figure 6.5. Milling parts with internal details has certain additional requirements. The main requirement is that there is sufficient unmachined area near the outer boundary of the part for clamping. Without sufficient unmachined area, the fixturing system would have to hold the part on the machined surfaces. The solution generated by the software is illustrated in Figure 6.6.

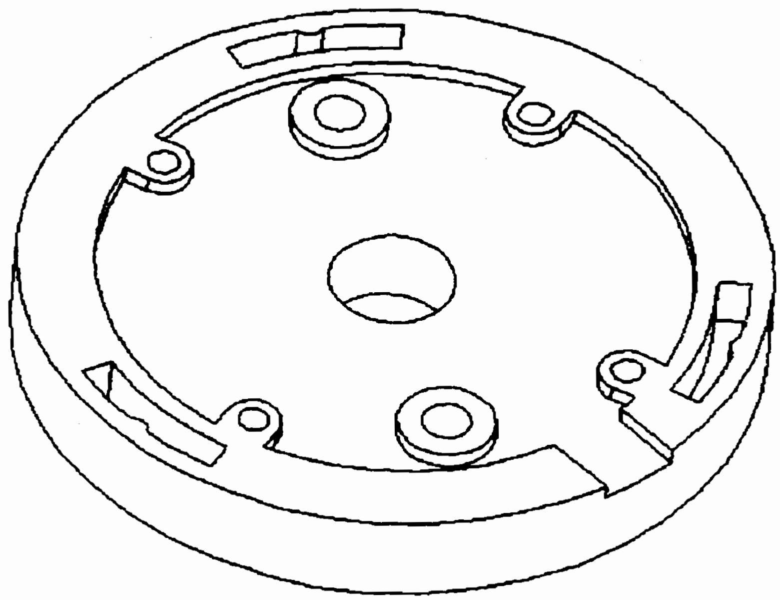

Figure 6.5 3-d view of a circular part with surface details

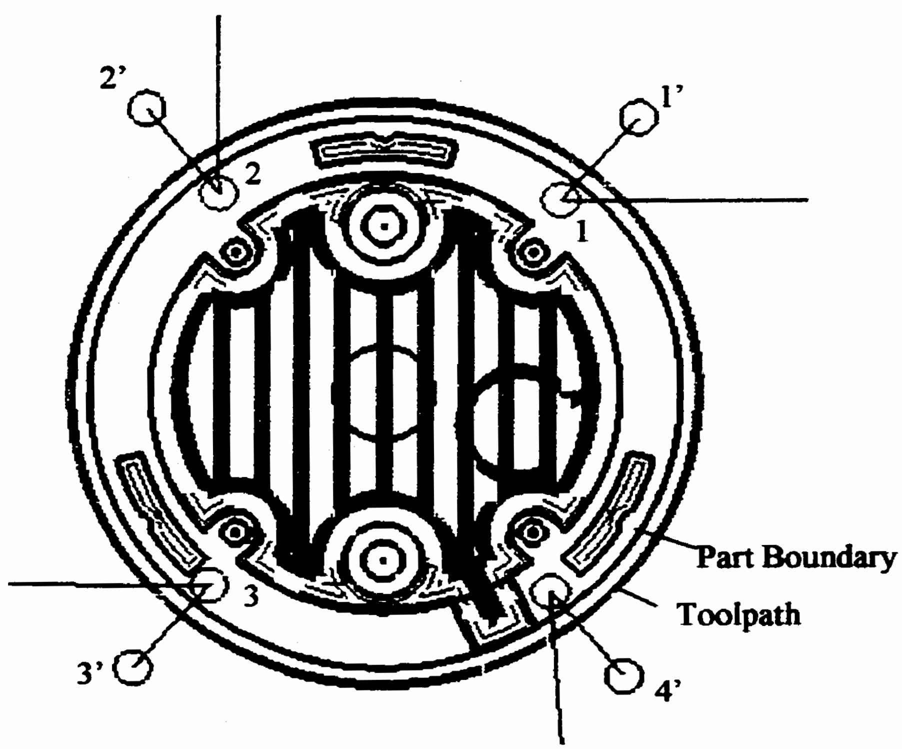

Figure 6.6 Circular part with its surface details

The following example, shown in Figure 6.7, illustrates a triangular part with internal details. Fitting four clamping points as far apart as possible in a triangle demonstrates that it is necessary to establish a minimum distance between the clamps. If no minimum separation is specified, the algorithm attempts to place two clamps in one corner. The separation must be sufficient to allow the interfering clamp to return to its clamping location before the next clamp interferes.

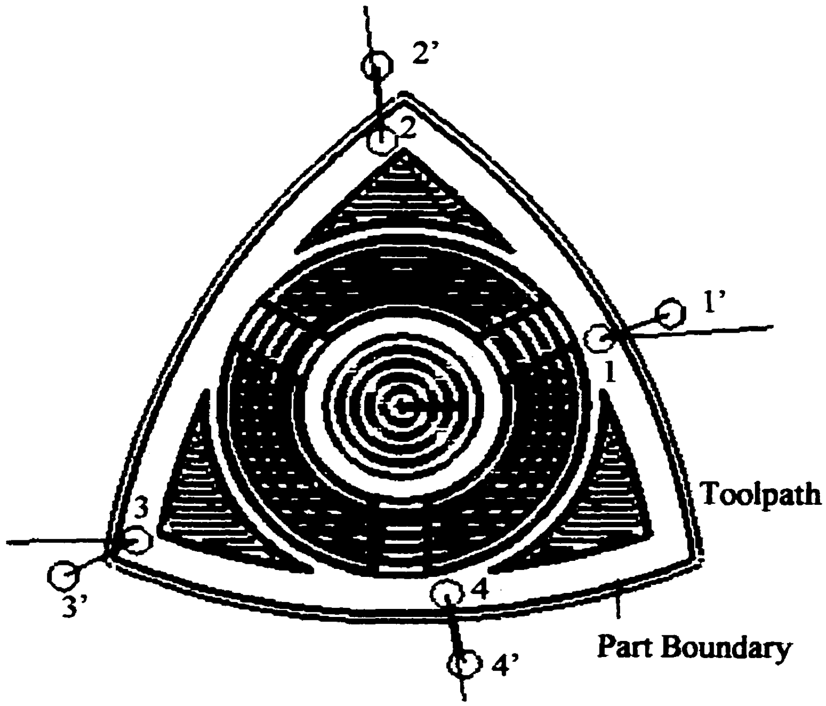

Figure 6.7 Triangular Part

The model of the clamping system that has been developed proves the feasibility of the system and demonstrates the potential robustness of the approach. The algorithm to determine clamping locations is able to successfully identify potential clamping locations for a large variety of planar parts. A major limitation of the algorithm is the requirement that an unmachined area be present around the periphery of the part.

6.3 Recommendations

The developed model of the automated fixturing system has demonstrated the feasibility of building a fixturing system capable of allowing uninterrupted milling operations. In particular, the system identifies specific issues that must be addressed to develop a fully working prototype.

The automated fixturing system identifies the difficulties of interfacing the clamping system with the milling system. Co-ordinating the actions of two separate systems adds a great deal of complexity to the problem which could be eliminated by integrating the milling machine and clamping control programs. Integrated control of the fixturing and milling machine would allow different clamping strategies such as different clamping locations during different stages of machining. The use of such a strategy could overcome a major limitation of the present clamping location algorithm where the clamping locations are restricted to unmachined areas around the periphery of the part.

The application of stepper motors in the fixturing system has proven adequate for this feasibility study. The response time of the fixturing system is a limiting factor of the milling machine's feedrate. Servo motors have a faster response time and a higher torque than stepper motors and, therefore, they should be used to develop a more refined prototype. The use of servo motors in an integrated system would allow the software to account for the speed of repositioning in the fixturing process.

The current algorithm is based on the part geometry. To further enhance the power of the fixturing system force analysis should be added. The force analysis should incorporate such aspects as stability of the part, machining and clamping forces, and vibration.

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Appendix A

Example IGES file kangbck.igs

```
S0000001
1H,,1H;,23HMASTERCAM version 6.13a,12HKANGBACK.GE3,9HMASTERCAM,1H1,16,8,G0000001
24,8,56,,1.,2,2HMM,1,0.01,13H000116.140242,0.00005,100.,,,8,0,;         G0000002
     110       1       1       1       1               0        00000000D0000001
     110       0       3       1       0                                       0D0000002
     110       2       1       1       1               0        00000000D0000003
     110       0       3       1       0                                       0D0000004
     110       3       1       1       1               0        00000000D0000005
     110       0       3       1       0                                       0D0000006
     110       4       1       1       1               0        00000000D0000007
     110       0       3       1       0                                       0D0000008
     110       5       1       1       1               0        00000000D0000009
     110       0       3       1       0                                       0D0000010
     110       6       1       1       1               0        00000000D0000011
     110       0       3       1       0                                       0D0000012
     124       7       1      38       0               0        00010000D0000013
     124       0       3       1       0                                       0D0000014
     100       8       1       1       1              13        00000000D0000015
     100       0       3       1       0                                       0D0000016
     100       9       1       1       1              13        00000000D0000017
     100       0       3       1       0                                       0D0000018
     110      10       1       1       1               0        00000000D0000019
     110       0       3       1       0                                       0D0000020
     100      11       1       1       1              13        00000000D0000021
     100       0       3       1       0                                       0D0000022
     110      12       1       1       1               0        00000000D0000023
     110       0       3       2       0                                       0D0000024
     100      14       1       1       1              13        00000000D0000025
     100       0       3       2       0                                       0D0000026
     100      16       1       1       1              13        00000000D0000027
     100       0       3       2       0                                       0D0000028
     110      18       1       1       1               0        00000000D0000029
     110       0       3       1       0                                       0D0000030
     110      19       1       1       1               0        00000000D0000031
     110       0       3       1       0                                       0D0000032
     100      20       1       1       1              13        00000000D0000033
     100       0       3       1       0                                       0D0000034
     110      21       1       1       1               0        00000000D0000035
     110       0       3       1       0                                       0D0000036
     110      22       1       1       1               0        00000000D0000037
     110       0       3       1       0                                       0D0000038
     100      23       1       1       1              13        00000000D0000039
     100       0       3       1       0                                       0D0000040
     110      24       1       1       1               0        00000000D0000041
     110       0       3       1       0                                       0D0000042
     100      25       1       1       1              13        00000000D0000043
     100       0       3       1       0                                       0D0000044
     110      26       1       1       1               0        00000000D0000045
     110       0       3       1       0                                       0D0000046
     100      27       1       1       1              13        00000000D0000047
     100       0       3       2       0                                       0D0000048
     110      29       1       1       1               0        00000000D0000049
     110       0       3       1       0                                       0D0000050
     110      30       1       1       1               0        00000000D0000051
     110       0       3       2       0                                       0D0000052
     100      32       1       1       1              13        00000000D0000053
     100       0       3       2       0                                       0D0000054
     110      34       1       1       1               0        00000000D0000055
     110       0       3       1       0                                       0D0000056
110,1.5,53.4067825013,0.,1.5,21.,0.;                                   1P0000001
110,14.,0.,0.,0.,0.,0.;                                                3P0000002
110,15.,1.,0.,15.,23.,0.;                                              5P0000003
110,15.,23.,0.,18.,23.,0.;                                             7P0000004
110,18.,23.,0.,18.,7.,0.;                                              9P0000005
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110,20.,5.,0.,20.4,5.,0.;                                              11P0000006
124,1.,0.,0.,0.,0.,1.,0.,0.,0.,0.,1.,0.;                               13P0000007
100,0.,20.,7.,18.,7.,20.,5.;                                           15P0000008
100,0.,14.,1.,14.,0.,15.,1.;                                           17P0000009
110,24.4,41.4880394902,0.,24.4,9.,0.;                                  19P0000010
100,0.,20.4,9.,20.4,5.,24.4,9.;                                        21P0000011
110,6.2770091403,55.8238548037,0.,23.5846727602,43.0994210252,         23P0000012
0.;                                                                    23P0000013
100,0.,22.4,41.4880394902,24.4,41.4880394902,23.5846727602,            25P0000014
43.0994210252;                                                         25P0000015
100,0.,4.5,53.4067825013,6.2770091403,55.8238548037,1.5,               27P0000016
53.4067825013;                                                         27P0000017
110,-15.,23.,0.,-18.,23.,0.;                                           29P0000018
110,-18.,23.,0.,-18.,7.,0.;                                            31P0000019
100,0.,-20.,7.,-20.,5.,-18.,7.;                                        33P0000020
110,-14.,0.,0.,0.,0.,0.;                                               35P0000021
110,-15.,1.,0.,-15.,23.,0.;                                            37P0000022
100,0.,-14.,1.,-15.,1.,-14.,0.;                                        39P0000023
110,-20.,5.,0.,-20.4,5.,0.;                                            41P0000024
100,0.,-20.4,9.,-24.4,9.,-20.4,5.;                                     43P0000025
110,-24.4,41.4880394902,0.,-24.4,9.,0.;                                45P0000026
100,0.,-22.4,41.4880394902,-23.5846727602,43.0994210252,-24.4,         47P0000027
41.4880394902;                                                         47P0000028
110,-1.5,53.4067825013,0.,-1.5,21.,0.;                                 49P0000029
110,-6.2770091403,55.8238548037,0.,-23.5846727602,43.0994210252,       51P0000030
0.;                                                                    51P0000031
100,0.,-4.5,53.4067825013,-1.5,53.4067825013,-6.2770091403,            53P0000032
55.8238548037;                                                         53P0000033
110,-1.5,21.,0.,1.5,21.,0.;                                            55P0000034
S0000001G0000002D0000056P0000034                                        T0000001
```
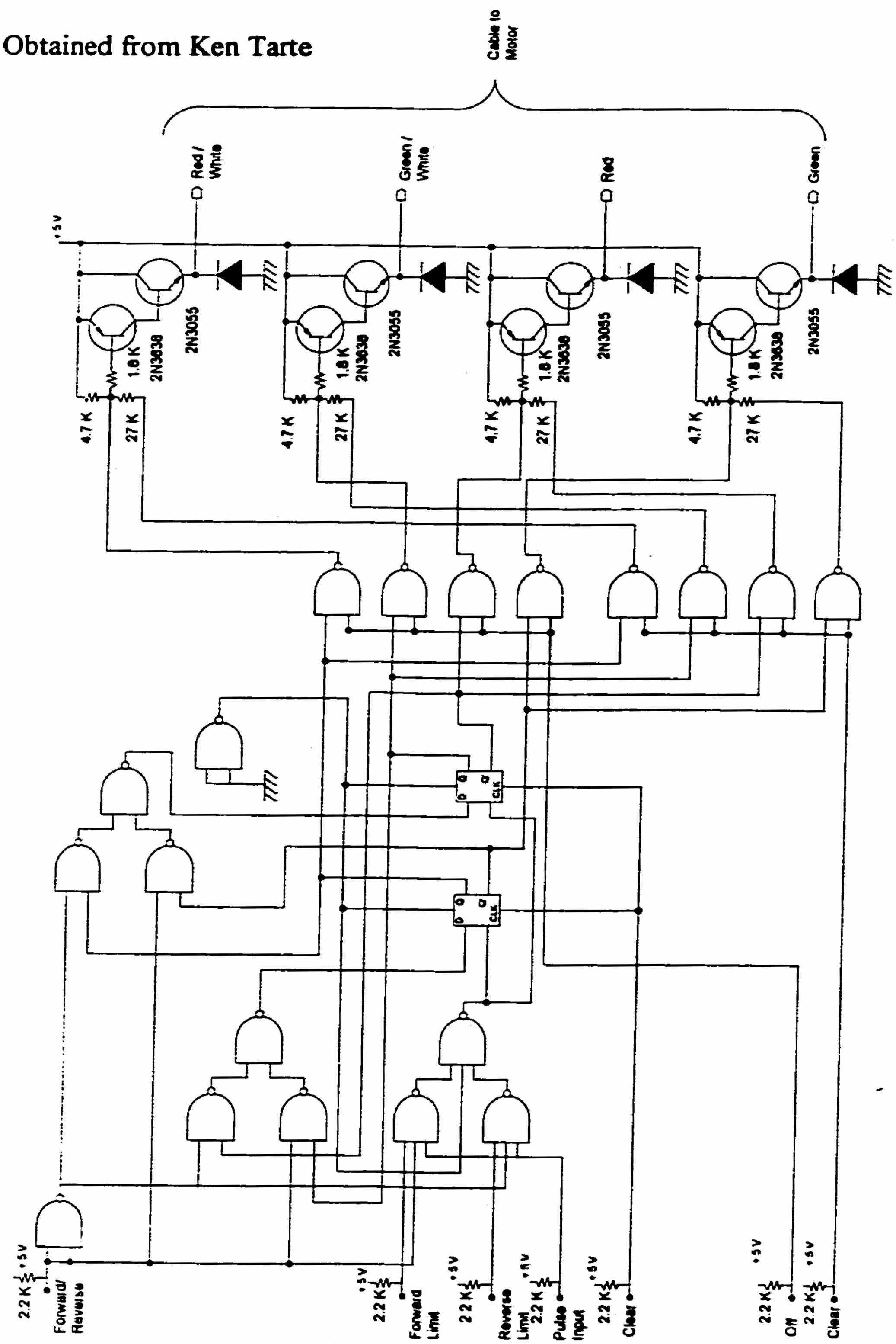
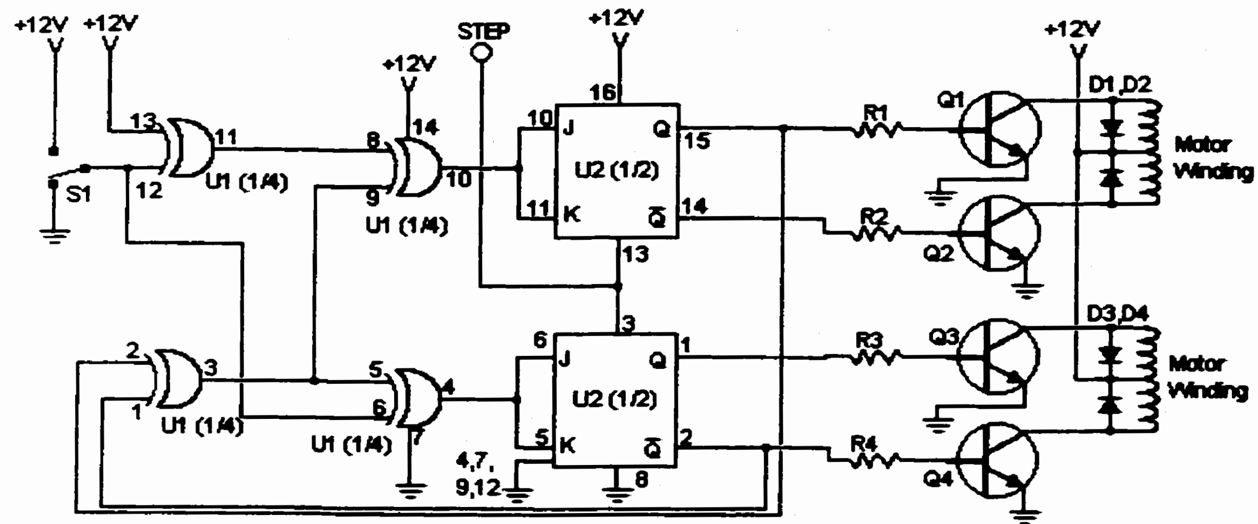

Appendix B

Stepper Motor Controller Circuit 1

Obtained from Ken Tarte



Stepper Motor Controller Circuit 2



U1	4070 CMOS XOR Integrated Circuit
U2	4027 CMOS Flip Flop
S1	Direction Switch
R1, R2, R3, R4	1K 1/4W Resistor
D1, D2, D3, D4	1N4002 Silicon Diode
Q1, Q2, Q3, Q4	2N3055 Transistor

This circuit was obtained from http://www.aaroncake.net/circuits/stepper.htm as a simpler alternative to circuit 1.

Appendix C

Sample NC File kangbck.nc

```
%
(PROGRAM NAME - KANGBACK )
(DATE, Day-Month-Year - 11-01-00  TIME, Hr:Min - 09:06 )
( TOOL - 02   DIA. OFF. - 02   LENGTH - 02   DIA. - 2.3800   2D-CONTOUR
)
N1 G00 G40 G49 G80 G90
/ N2 G91 G28 Z0.
/ N3 G28 X0. Y0.
N4 G0 G90 X-25.59 Y41.488 S2500 M3
N5 Z30.
N6 G1 Z-.5 F500.
N7 Y9.
N8 G3 X-20.4 Y3.81 I5.19 J0.
N9 G1 X-20.
N10 G3 X-16.81 Y7. I0. J3.19
N11 G1 Y21.81
N12 X-16.19
N13 Y1.
N14 G3 X-14. Y-1.19 I2.19 J0.
N15 G1 X0.
N16 X14.
N17 G3 X16.19 Y1. I0. J2.19
N18 G1 Y21.81
N19 X16.81
N20 Y7.
N21 G3 X20. Y3.81 I3.19 J0.
N22 G1 X20.4
N23 G3 X25.59 Y9. I0. J5.19
N24 G1 Y41.488
N25 G3 X24.2896 Y44.0582 I-3.19 J0.
N26 G1 X6.9819 Y56.7826
N27 G3 X.31 Y53.4068 I-2.4819 J-3.3758
N28 G1 Y22.19
N29 X-.31
N30 Y53.4068
N31 G3 X-6.9819 Y56.7826 I-4.19 J0.
N32 G1 X-24.2896 Y44.0582
N33 G3 X-25.59 Y41.488 I1.8896 J-2.5702
N34 G0 Z30.
N35 M05
N36 G91 G28 Z0.
N37 G90
N38 M30
%
```