AUTOMATED FIXTURE AND ROBOT AIDED DEBURRING FOR LIGHT AIRCRAFT COMPONENTS

by

Jayasundaram Pandian

A Thesis
Submitted to the Faculty of Graduate Studies
in Partial Fulfillment of the Requirements
for the Degree of

Master of Science

Department of Mechanical and Industrial Engineering
University of Manitoba
Winnipeg, Manitoba
CANADA R3T 2N2

0-612-32211-4

THE UNIVERSITY OF MANITOBA

FACULTY OF GRADUATE STUDIES

*****

COPYRIGHT PERMISSION PAGE

AUTOMATED FIXTURE AND ROBOT AIDED DEBURRING FOR LIGHT AIRCRAFT COMPONENTS

BY

JAYASUNDARAM PANDIAN

A Thesis/Practicum submitted to the Faculty of Graduate Studies of The University

of Manitoba in partial fulfillment of the requirements of the degree

of

MASTER OF SCIENCE

Acknowledgments

I wish to thank my advisors Dr. S. Balakrishnan and Dr. N. Popplewell for their relentless effort to acquire this project as well as financial support from Bristol Aerospace Limited (BAL), Winnipeg. I also wish to thank them for their endless patience, advice and encouragement that lead me to complete this project sucessfully.

I wish to thank Mr. Ken Tarte for all the technical support he rendered at the CIM and Automation Laboratory. I also wish to thank Mr. Irwin Penner for all the technical support he rendered at the Machine Shop Laboratory.

I wish to thank the management of Bristol Aerospace Limited, Winnipeg, for providing me with the opportunity to pursue this project and also for their financial support. In particular, I wish to thank Mr. Ravi Rai of BAL for his endless efforts in creating this opportunity and also for his thankless help in making the R&D facility at BAL available to carryout this project. I also wish to thank Mr. Norman Richards, Ms. Kristin Johnson, Mr. Dale Newsham and Mr. Ian Stevenson for their technical support at BAL throughout the course of this project.

I thank my parents in India for their endless moral support, prayers and encouragement throughout the course of my study at the University of Manitoba, Winnipeg. Last but not the least, I thank my wife, Sumadhi, for being by my side during hard times and supporting me patiently, by all means possible, throughout my period of study.

Abstract

Bristol Aerospace Limited (BAL), Winnipeg, manufactures a wide range of parts for the Boeing-777 aircraft. Most of these parts have cubic edges and cubic surfaces in order to form a family of non-prismatic parts. These parts vary widely in size, geometry and complexity. BAL requires all the Boeing-777 parts to be deburred, and also, all the part's edges to be rounded uniformly with a radius within 0.02" to 0.04". This is a tedious task which is presently performed manually. It was identified as one of the most appropriate and cost effective applications for robotic machining. The deburring and finishing operations require fixtures that hold the parts while they are processed. The focus of this thesis has two components: automated deburring as well as automated fixturing of the parts to be deburred. The fixture should be flexible enough to accommodate as many parts as possible in order to reduce the otherwise tedious setup time. Also, the fixture should be modular so that the fixture's configuration can be assembled expeditiously for any given fixturable part. The functions of the different modules of the fixture system must also be controlled selectively and efficiently with the help of programmable devices. The thesis focuses on (i) investigating the suitability of the FANUC-S12 robot for the operations mentioned, (ii) evaluating and identifying the required deburring tools to perform the deburring operations, (iii) defining a suitable deburring methodology, and (iv) developing a reconfigurable fixture controlled by programmable devices. The results indicate that automated robotic deburring is feasible and cost effective.

Table of Contents

			Page
	Acknowledgments		ii
	Abstract		iii
	List of Figures		vi
	List of Tables		viii
1.	**Introduction**		1
	1.1	Overview of the problem	1
	1.2	Scope of the problem	4
	1.3	Organization of the thesis	6
2.	**Literature Review**		7
	2.1	Automated fixtures	7
	2.2	Automated deburring	21
3.	**Burrs and Deburring**		24
	3.1	Introduction	24
	3.2	Effects of burrs	25
	3.3	Deburring process	26
	3.4	Deburring tools	29
	3.5	Commercial tools	36
	3.6	Conclusion	39
4.	**Automated Fixture System**		40
	4.1	Introduction	40

4.2 Proposed fixture system 42

4.3 Fixture stability 50

4.4 Location selection of fixture components 55

4.5 Fixture control 69

4.5.1 Operation of fixture control 69

4.5.2 Overall cell control 83

5. Results 84

5.1 Deburring results 85

5.2 Fixturing results 90

6. Conclusions and Recommendations 92

6.1 Conclusions 92

6.2 Recommendations 92

References 94

Appendix-A Evaluation of Fanuc -S12 Robot's Performance 98

Appendix-B Evaluation of Fanuc-S12 Frame Shift Capability 109

Appendix-C Computation of Clamping Locations 119

List of Figures

Figure	Page
Figure 3.1: Reprcsentative part	28
Figure 3.2: Cylindrical abrasive tool	32
Figure 3.3: Circular disc abrasive tool	33
Figure 3.4: Constant force device	34
Figure 3.5: String brush	36
Figure 4.1: Robotic deburring cell	42
Figure 4.2: Base plate	44
Figure 4.3: Supporter module	46
Figure 4.4: Horizontal locator	47
Figure 4.5: Horizontal clamp	49
Figure 4.6: Analysis of workpiece forces	52
Figure 4.7: Representative part for force analysis	54
Figure 4.8(a): Pin locations for part representative of group-1	58
Figure 4.8(b): Pin locations for part representative of group-1	59
Figure 4.8(c): Pin locations for part representative of group-2	61
Figure 4.8(d): Pin locations for part representative of group-3	62
Figure 4.8(e): Pin locations for part representative of group-3	62
Figure 4.8(f): Pin locations for part representative of group-3	63
Figure 4.8(g): Pin locations for part representative of group-4	64
Figure 4.8(h): Supporter and locator pin locations on the fixture table	67

Figure 4.9(a) - 4.9(h): PLC logic to control the fixture 74 - 81

Figure 5.1: Digital I/O interface of FANUC-S12 91

Figure A1: Experimental setup for accuracy test 100

Figure A2: Experimental setup for repeatability test 104

Figure B1: Experimental setup to find FANUC-S12 frame shift 110

Figure C1: Part for computation of clamping locations 119

List of Tables

Table	Page
Table 4.1: Computed and actual clamping distances	65
Table 4.2: Supporter and locator pin coordinates on the fixture table	68
Table 4.3: Supporter requirements for four sample parts	72
Table 4.4: PLC input assignment	73
Table 4.5: PLC output assignment	73
Table 5.1: Robot programming time	87
Table 5.2: Processing time	88
Table 5.3: Manual processing time based on recent history	89
Table A1: Results of accuracy test along X-axis	101
Table A2: Results of accuracy test along Y-axis	102
Table A3: Repeatability results	105
Table A4: Backlash results	108
Table B1: Origin of user frame locations on the fixture table	111
Table B2: Origin coordinates of user frame	112
Table B3: Tip position vector in user frame	114
Table B4: Position errors	115
Table B5: Dowel pin locations on the fixture table in user frame	116
Table B6: Origin locations on the fixture table	116
Table B7: Test locations in user frame	117
Table B8: Positional errors	118

CHAPTER-1 Introduction

1.1 Overview of the problem

Burr is a collective term that can be related to the presence of any unwanted projection of material on the edge or surface of a machined workpiece. A burr is formed as a result of the plastic flow of the workpiece material which undergoes a plastic deformation during cutting, forming, blanking or shearing. The presence of the burr on a machined part creates an unsafe material handling environment, resulting in a health and safety problem. Operators may receive injuries such as laceration and deep cuts. The burr also induces misalignments during product assembly. The products assembled with such parts will possess low quality and they may become functionally inefficient. Deburring and edge finishing are often critical for the correct fit, assembly and function of products, especially for precision parts. Therefore, the elimination of the burr has become an utmost necessity in all manufacturing industries to ensure safer handling of parts and to improve the quality, functionality and the appearance of the finished product.

All machined parts invariably have razor sharp edges in addition to the undesirable burr. Burrs are generated in random sizes and shapes that vary from a small sliver to a large flash. Hence, the basic deburring process includes breaking these sharp edges in addition to eliminating the burr. Most industries ensure that the parts they produce undergo a basic deburring process. Some industries require their products to be chamfered in addition to the basic deburring. Others require their products to possess rounded edges with the radii within a specific range. Rounded edges are particularly desired on parts that are subjected to varying stress levels. Failure to round these edges may lead to edge cracking and subsequent product failure. The basic manual deburring process is tedious, difficult and hazardous. The deburring process becomes more difficult and time consuming as the complexity of the part increases. The final finish is often variable. Also, as the deburring requirements on a part increase, the process becomes more hazardous, time consuming, labour intensive and very expensive. Also, manual deburring demands a very high level of skill and experience to maintain consistency and the product's quality. This is particularly true when metal parts are being manufactured to close tolerances.

Most industries perform burr removal operations manually. A variety of hand-held rotary tools and portable power tools are used in the operation. Hand-held tools are also used to produce the required chamfer and rounded edges. These hand-held rotary tools vibrate continuously during deburring. Such work environments may cause repetitive strain injury and lead to adverse health conditions such as the "white finger" condition and the "carpal tunnel syndrome". Replacing such a troublesome manual deburring process with a sufficiently accurate, automated alternative has proved to be a real challenge. An automated deburring system will have the potential to consistently produce high quality finishes and greater part uniformity when equipped with the proper tooling and methodology.

The deburring operation carried out on a workpiece, either manually or by automation, has the potential to damage any previously machined surface or to void the established, precision dimensions of the workpiece. Deburring should be restricted to the removal of the unwanted material alone. This constraint initiates the demand for a suitable work holding device or a fixture. A fixture can be considered as a production tool that locates and securely holds a workpiece so that the required manufacturing operations can be performed. Such a work holding device or fixture should possess properties such as positive location, rigidity, repeatability, ruggedness, low profile and reliability. The fixture should be tolerant to minor variations in the workpiece's dimensions. Also, the fixture's clamping forces should not cause any bending or damage to the workpiece. Fixtures can be either custom developed from available tools to be dedicated fixtures or they can be assembled from a toolkit of precisely manufactured fixture elements to be modular fixtures. The second option allows flexibility through reconfiguration.

Fixtures can be custom designed to locate and hold a workpiece when the workpiece's shape, desired position and orientation are specified. Typically, the designer combines intuition with trial and error to design such dedicated fixtures. Dedicated fixtures imply that they have been designed for a specific workpiece geometry and manufacturing operation. Dedicated fixtures are generally very expensive to manufacture and they are most suitable for mass production where their costs can be absorbed by the large number of products produced. These custom designed fixtures are extremely intolerant to any variations in the workpiece's shape or dimensions. Also, they require to be re-designed and re-manufactured every time the workpiece design is altered. These fixtures are developed either for a specific purpose or they are limited to a number of applications so that they are incapable of handling families of parts. Hence, they are unsuitable for small batch production. Also, this fixturing approach could cause a long lead time and high manufacturing cost in a small batch production environment.

Reconfigurable fixtures imply that they have been designed for a family of workpiece geometry and manufacturing operations. These fixtures are most suitable for batch production and job-shop environments, where they can be used for many different products. Such reconfigurable fixtures should possess properties such as modularity, automatic reconfigurability, sensory feedback controllability and programmability. Fixturing encompasses the design and assembly of such devices for locating and immobilizing a workpiece during manufacturing. Fixturing also accounts for typically 10-

20% of the total manufacturing costs [9] so that automation is greatly desired by any industry.

The problem of automating the deburring process, combined with the problem of designing an automated reconfigurable fixture for a family of parts, has become a dual problem. Arriving at a solution for this dual problem has proved to be a real motivating challenge.

1.2 Scope of the problem

Bristol Aerospace Limited (BAL), Winnipeg, manufactures a wide range of parts for the Boeing-777 aircraft. These parts are machined with a very close tolerance in a three spindle, Computer Numerically Controlled (CNC) gantry mill. The stock is a rectangular block of aluminum alloy. Three identical parts are produced in any given cycle. The Boeing-777 parts that are produced at BAL have unique part features such as a web, side flanges and cross ribs. Although machined from large aluminum stock, these parts possess very thin walls with the wall thickness ranging between 0.1" to 0.25". Most of the Boeing-777 parts possess cubic edges and cubic surfaces. Therefore, the parts cannot be classified as a family of prismatic parts. The parts also vary widely in size, geometry and complexity

BAL requires all the Boeing-777 parts to be deburred and, also, all the part's edges to be rounded uniformly with a radius within 0.02" to 0.04". BAL also requires all a part's surfaces to be finished with the surface roughness not exceeding 125 microns, and, the surface mismatch between adjacent tool paths must not exceed 0.01". BAL also requires random and unpredictable tool marks and kellering marks to be blended.

The machined Boeing-777 parts undergo several operations before being shipped. All parts undergo dimensional inspection (DI) on a coordinate measuring machine (CMM) immediately after being machined. These parts have to be deburred initially to enable safe handling prior to the dimensional inspection. After the DI, the parts are scribed. The lugs and tabs are removed by a routing operation. The parts then undergo surface inspection (SI), using a liquid penetrant inspection (LPI) process, to detect the presence of any surface cracks. The parts are then deburred to produce the rounded edges and the part surface is blended. Once again, the parts undergo dimensional inspection on the CMM followed by a visual inspection of the deburred edges and surfaces. The parts are then shot peened and inspected on the CMM. Finally, the parts are anodized and painted prior to shipping.

Presently, the edge deburring, edge rounding and surface blending operations are performed manually by using various hand-held, rotary tools. Sand filled bags are used to mount and hold the parts on the workbench in order to reduce the vibration during the processing operation. This tedious task of deburring complex parts was identified as one of the most appropriate and cost effective applications for robotic machining. The FANUC-S12, articulated robot located at BAL's research facility was available to automate the deburring process. The reliable performance of robot aided deburring depends on the accuracy and repeatability of the robot utilized. The performance of the deburring system also depends on the performance of the deburring tools. Hence, the robot as well as the deburring tools have to be evaluated first. The appropriate tools can be selected based on the result of a tool evaluation. The deburring methodology can then be developed based on the tools selected for deburring. The Boeing-777 part family comprises 40 different parts that need to be deburred. The deburring and finishing operations require fixtures that hold the complicated parts while processing. As the Boeing-777 parts vary widely in size and shape, the fixture should be flexible enough to accommodate most of the parts. Also, the fixture should be modular so that the fixture's configuration, for any given fixturable part, can be assembled expeditiously. The functions of the different modules of the fixture system must also be controlled selectively and efficiently with the help of programmable devices.

The scope of this thesis is: to investigate the suitability of the FANUC-S12 robot for the automated deburring; to identify and evaluate the performance of the deburring and rounding tools; and to develop a reconfigurable fixture controlled by programmable devices.

1.3 Organization of the thesis

A literature review of the field of deburring as well as the field of automated fixturing is presented in Chapter 2. The concept of the burr as well as the deburring tool evaluation and selection are presented in Chapter 3. The proposed fixture system and the aspects related to automated control and selection of the fixture component locations are presented in Chapter 4. The deburring process and the operational details of the developed fixture are given in Chapter 5. Finally, conclusions and recommendations are presented in Chapter 6. The Fanuc-S12 performance evaluation results are presented in Appendices A and B. A sample computation to determine the fixture component locations is presented in Appendix C. As BAL's CAD data uses SI units, all part dimensions are presented in SI units. As the robot's controller uses metric units, all robot positions are presented in metric units.

CHAPTER-2 Literature Review

The problem investigated in this thesis has two components: automated deburring and automated fixturing of the parts to be deburred. Aspects related to fixturing have been researched widely. However, very few scientific research papers related to automated deburring have been published. Robotic deburring applications are generally discussed only in trade and promotion literature. This chapter will present a review of the pertinent literature.

2.1 Automated Fixtures

Most manufacturing, assembly and inspection operations require fixtures to locate and hold parts. Typically, the designer's intuition and experience results in custom designed fixtures for a specific part. Such dedicated fixtures are most suitable for mass production environments. However, part design is subject to change and, hence, the necessary fixtures may have to be redesigned and re-fabricated. Fixture fabrication costs may be reduced considerably by constructing the fixture from re-usable modular elements. Traditionally, the plan for the design of a modular fixture consists of the manual selection of fixture elements that is based largely upon the specification of the workpiece and the process to be carried out on the workpiece. The criteria of fixture element selection are to simplify the fixture setups, increase the manufacturing efficiency, achieve collision free motion of the tool over the workpiece, ease the process of fixture loading and unloading and ensure accurate and repeatable workpiece positioning (i.e., its location and orientation).

Reconfigurable fixturing systems have a variety of standard fixture elements such as locators, vertical supporters, horizontal clamps, vertical clamps, V-blocks and a base plate. These elements are modularized to rigidly fasten a variety of workpieces. A modular fixture is an arrangement of such fixture elements that will locate and hold a given part securely on the base plate. There are two types of modular fixturing systems currently in use, namely, the dowel-pin system and the T-slot system. The dowel-pin system employs a base plate that is equipped with alternating dowel and tapped holes. These holes are aligned along the longitudinal and lateral directions of the base plate with accurate spacing between adjacent holes. The fixture elements used in the dowel-pin system are designed to be assembled onto the base plate by using the dowel holes. The T-slot system employs a base plate that is equipped with several perpendicular and parallel precision spaced, T-slots on its surface. The dowel-pin base plate is generally preferred over the T-slot type base plate in most applications because it offers the ability to locate a part precisely, it is highly repeatable, facilitates quick assembly of the various fixturing components, facilitates a quick change of the fixturing components for different parts and also, it allows the re-use of fixturing components for a variety of parts. Moreover, the assembly sequence of the fixture elements has to be considered more carefully on a T-slot type base plate than on a dowel-pin type base plate, especially when the fixture elements are assembled on the same row of slots.

Trappey et al., [1] reviewed a wide range of fixturing concepts to reveal the progress in the field of fixture design since 1980. Most of the research in automated fixture design emphasizes eliminating human intervention and enhancing computerized automation. The review indicates that the use of rule based, fixture design systems has been developed primarily for prismatic parts. Also, the review indicates that fixturing systems have been developed for very specific workpieces such as thin walled plates, turbine blades, simple prismatic parts, two phase fluid beds, magnetic base-plate modular fixtures for sheet metal drilling and routing, and conformable fixtures. The general conclusion made in this review is that a comprehensive automatic fixture design system has not been fully developed.

Research related to the hardware aspects of fixtures has resulted in several alternative designs. A few designs have focused on sensor integration for automated fixturing. Extensive research carried out in automated fixture design has resulted in the development of heuristic search techniques and exhaustive algorithms to generate and test fixture designs with a limited number of fixturing components. The results of the literature survey can be categorized broadly into the following categories: basic hardware design, heuristics, application of expert systems and computer aided tools for the design and evaluation of fixtures. These topics are presented separately in the following sections.

2.1.1 Fixture hardware design

Benhabib et al., [2] developed a modular programmable fixturing system (MPFS) specifically for robotic assembly. A set of sensor integrated, modular fixturing components with built-in flexibility was developed for the vertical assembly of workpieces. The sensor integration is intended to verify the proper insertion of the fixturing components, detect the presence of the workpiece and to control the clamping process. The built-in flexibility and modularity were achieved through the structural design of the fixture components. Programmability was accomplished through a personal computer with the necessary interface cards to control the clamping processes. Forces produced during machining operations were not considered.

Liu [8] proposed a method to change dedicated fixturing systems into a modular fixturing system. The methodology demonstrated that the fixturing functions (locating, supporting, clamping, guiding and linking) provided by a dedicated fixture, can be attained with a set of modular fixturing elements. The fixturing functions accomplished by the dedicated fixtures were identified as modules of modular fixturing functions and they were collected in their functional groups. A fixture mapping strategy was developed to determine the set of appropriate modular fixturing elements that can replace the dedicated fixture. The design process was iterative. The completed modular fixture design must be checked and refined until it is satisfactory.

Shirinzadeh [9] developed a modular fixturing kit and a software tool to design, analyze and interactively verify the fixture layout in a computer aided design environment. The system was designed specifically for flexible fixtures in robotic assembly. The modular fixturing kit comprised an electromagnetic base plate, locators, supporters as well as vertical and horizontal clamps. Flexibility was attained by examining the structural design of the fixturing modules. The design of the fixture layout was performed interactively on a CAD based package. The kinematic analysis of the fixture layout was carried out automatically by a dedicated module in the software program. The software also generated the robot program to set up and change the fixture layout and to automatically perform the assembly operations.

Ponce [11] proposed, but did not implement, a three dimensional fixturing device and an algorithm to enumerate all the possible fixtures for solely polyhedral parts. The study was restricted to four point, frictionless contact modular fixtures. The fixturing device had two parallel plates and a set of locators. Each plate had an array of evenly spaced, dowel holes. The distance between the two plates could be adjusted continuously. The algorithm enumerated the set of all locator configurations that achieve static equilibrium through contacts with the selected faces of the workpiece. The orientation of the part was computed for each selected locator configuration. The immobilization condition was tested for each part orientation and the associated locator configuration.

Chan et al., [16] developed a CNC multi-finger module that combined modularity and computer numerical control in the design of flexible fixtures. They also reviewed the mechanical design aspects and the operation of the module. The multi-finger module was designed as the only fixturing component that provided all the locating, supporting and clamping functions. The computer numerical control of this structurally complicated, multifunction module allowed direct programming and control of the fixturing without the need for an external device. Different fixture configurations were achieved by different combinations of a multiplicity of such modules. The fixture could be reconfigured, by using numerical control, to accommodate any change in the part's geometry without altering the locations of the modules providing the change was within the adjustable limit of the fingers.

Wagner et al., [20] proposed a modular fixturing system and an algorithm to synthesize the fixtures. The modular fixturing system possesed seven adjustable length struts composed of discrete length segments, an adjustable ball tip and a four walled, rectangular frame with a lattice of mounting sockets arranged on the frame's walls. The algorithm accepted a CAD model of a polyhedral part and the desired three dimensional orientation of the part as input. Then it synthesized a set of fixtures that kinematically restrain the part. These fixtures were then ranked based on their ability to resist a user specified load. The algorithm provided the ranked list of candidate fixtures as output. A fixture was specified by providing the length, the azimuth angle, the elevation angle, the wall and the lattice coordinates for each of the seven struts. These fixtures do not employ clamps. The part was loaded manually onto the fixture by initiating contact with several pre-positioned struts. Then the remaining struts were pivoted into place to take up the slack in the part's configuration. The angle that each strut made with the mounting wall had to be adjusted manually so that the strut extended normally to the associated contact surface of the part. This class of fixtures is appropriate for static loads that occur during assembly or inspection only. Also, this class of fixtures may be susceptible to dynamic disturbances that occur during the deburring considered in this study.

2.1.2 Heuristic based fixture design

Brost et al., [3, 5] developed an algorithm to find an optimal fixture (i.e., one that constrains a part with maximum form closure), if one exists, for a polygonal part. The problem was treated as a planar problem and a four point contact class of modular fixture was considered. The algorithm allowed the user to specify the geometrical access constraints that prevent the fixture from interfering with certain regions of the workpiece due to reasons such as cosmetic surfaces, clearance for grasping, machining, assembly and other operations. The polygonal part's boundary was provided as a list of vertices. The set of geometrical access constraints was given as a list of polygons in the part's coordinate frame. The optimal fixture design generated by the algorithm was proved to sufficiently constrain the planar motion of a part. However, the optimal fixture design was inadequate to completely constrain the part's three dimensional motions that arise, like chatter, from the cutting forces during the actual machining. The algorithm did not allow curved edges because only prismatic parts were considered. Also, the algorithm did not synthesize the redundant locators that were required to fully constrain the part's motions during machining.

Brost et al., [6] developed and implemented an algorithm to design fixtures and assembly pallets in order to locate and hold three-dimensional parts. Their work was an extension of the algorithm presented in [3, 5]. The fixture model consisted of three locators, three supporters, one horizontal clamp and three swing arm, top clamps. The algorithm accepted a CAD description of a prismatic part, a description of the machining operations, and a set of expected cutting forces as input. The planar fixture design was synthesized first by using the algorithm presented in [3, 5]. Then the supporter locations were enumerated based on the results from the first step. The top clamps were located directly above the vertical support points to avoid clamp induced deformations of the part. The final fixture designs were ranked on their ability to resist the expected applied forces without exerting large reaction forces on the part. As the methodology was developed by considering solely prismatic parts without curved edges, this approach is unsuitable for the class of parts considered in this study. An additional limitation was the use of overhead clamps which are, once again, unsuitable for parts that require deburring on their top surfaces.

Wallack [7] proposed alternative modular tool kits and two generic fixture design algorithms; namely, a dual fixture design algorithm and a heuristic fixture design algorithm. The tool kits included a jaw fixture which had a pair of fixture plates that can pivot like a pair of scissors, a three jaw fixture chuck which had three fixture plates mounted on the three jaws of a chuck, a four jaw fixture chuck which had four fixture plates mounted on the four jaws of a chuck and a three dimensional tetrahedral chuck which had four fixture plates mounted on the four jaws of a tetrahedral chuck. The dual fixture design algorithm was based upon the duality between the fixture design and indexing. Indexing is an object recognition technique based on sparse probe data. A set of linear distance sensing probes were employed to obtain the indexing coordinates. The indexing coordinates were discretized in order to obtain the indexing vector. The algorithm constructed an indexing table in a computer that contained the indexing vectors and their corresponding model features for every sensing configuration of a given part. The fixture configuration corresponding to each indexing table entry was verified, for stability, by using a force analysis. The most stable fixture configuration was finally selected. The heuristic fixture design algorithm identified candidate edge sets and then, for each edge set, searched for a configuration that achieved simultaneous contact and force closure.

Willy et al., [12]] developed software to design a fixturing system with the T-slot based modular fixturing kit. The algorithm determined and evaluated the optimal fixture configurations from the description of the polygonal workpiece and the assembly task. The main components of the algorithm were the selection and configuration of the stability planes and the evaluation of the selected fixture configurations. The input information was retrieved either from databases or given interactively by the user. The input data included the possible stability planes, the assembly wrench, the necessary assembly space, the geometry of the fixture elements and the geometry of the base plate. The algorithm transformed the curved surfaces into sets of polygons by using an approximation method. The combinations of stability planes which can stabilize the workpiece were determined. Each of these combinations represented a possible fixture configuration. Then the fixture element positions were determined for each configuration. Each of the generated fixture configurations was assessed by using a stability analysis and checked, by using a simulation program, for a possible collision. The stability analysis incorporated safety factors for possible failures such as overturn, translation, rotation as well as the workpiece lifting from its base plate. The most stable fixture design was selected.

Trappey et al., [14] developed a set of algorithms to determine the fixturing locations. They considered the orientation and geometry of a non-prismatic workpiece as well as the magnitude and direction of the cutting forces. The algorithm employed heuristic search techniques on the projected envelope of the workpiece to determine the locating and clamping points based on the 3-2-1 fixturing principle. The 3-2-1 fixturing principle states that three supporters in the primary plane; two locators in the secondary plane and one locator in the tertiary plane are sufficient to fixture any prismatic workpiece.

The algorithm utilized the boundary representation (B-rep obtained from the I-DEAS solid modeler) of the workpiece to determine the fixturing points. The orientation of the workpiece, as well as the magnitude and direction of the cutting forces were assumed to be known prior to the heuristic search. Although this algorithm was developed to determine the fixturing locations for a more general workpiece geometry, only the faces corresponding to the projected boundary edges that are perpendicular or parallel to the base plate were considered as candidate fixturing faces. Factors such as part distortion and cutter path interference were not considered. This algorithm did not guarantee the possibility of vertically clamping the workpiece at all the three selected vertical fixturing points although it was possible to support the workpiece at all three points.

2.1.3 Expert systems and computer aided fixture design

Lin et al., [15] developed an expert system, with artificial intelligence, to design fixtures for prismatic workpieces by using modular fixturing. The parameters needed by the designing process were input interactively. The workpiece geometry was drawn in Auto CAD. The input CAD data was converted into configuration data, based on the concept of topology. The configuration data comprised the point-line circular path data and the face-line circular path data. The positioning of the supporters, locators and clamps is based on the 3-2-1 fixturing principle. Contact between the workpiece and the fixture components was assumed to occur at points located in three dimensions. An integer programming method was used to individually select the fixturing positions in each basic plane. A static force balance analysis was performed on the resulting fixture design. The cutting force and clamping force were assumed to be known. The fixture design was considered acceptable if the reaction forces of all the locators were positive. Otherwise, corrections had to be made interactively until the reaction forces become positive. The expert system applied both experience and learned knowledge for positioning and clamping the basic planes. According to the configuration attributes and the data input, the expert system selected the basic planes for positioning as required. When the database failed to provide reasonable inferences, the system employed heuristic learning rules to obtain new knowledge. The learning method used rote-learning which integrates new knowledge into the system and optimized the experiential knowledge base. The heuristic rules were written in the if (condition) - then (action) form. The system has been developed for L, I, U and T shaped workpieces. Complex workpieces were not considered.

Young et al., [13] presented a method of integrating fixturing strategies with technological and geometric information to automate a setup planning for machining, within a product modeling environment. The method used a machine's capability (represented in terms of fixturing strategies, machining rules and machining operations) and product model analysis techniques to generate setup plans. Setup planning is concerned with identifying the setups to be used when machining. A setup plan describes the machining to be performed on a workpiece with the selection of the appropriate fixturing method. The setup planning problem for prismatic components machined from a solid rectangular block with setups that can be performed along orthogonal axes was considered. The workpiece descriptions were assessed against the machine's capability to identify an appropriate strategy which resulted in the generation of the required setup plans. A spatially divided, solid model was produced from the geometric representation and it was queried to provide the feature interaction data. The machine type was restricted to a three axis vertical machining center and the fixturing was assumed to be achievable from standard fixturing elements such as a vice, bolts and rectangular clamps. The product models were generated by using commercial CAD software.

Cabadaj [17] presented the theoretical aspects of the computer aided fixture design relevant to intelligent manufacturing. The data processing tasks involved the design and evaluation of the functional model and the creation of documentation for the fixtures. The relations between the workpiece and fixture elements were solved through a kinematic analysis in the design process. A rule based expert system was utilized in order to select the functional elements of a fixture based on the given information about the part's locating surfaces. The evaluation strategy computed the forces involved by using a force model and it compared these forces to the limited forces that can be applied on the fixture elements. The values of the cutting forces and moments were assumed to be known a priori. The number of fixture elements for a locating surface was determined from the calculated force. A fixture document was created for the fixture model, if the calculated forces were acceptable. The CAD-MBFS (computer aided design of a modular block fixturing system) concept was proposed for the creation of documents. This design procedure was based on replacing the functional elements of a fixture by components from a fixture catalogue.

Yu et al., [19] developed an algorithm to generate loading patterns for four point, frictionless contact planar fixtures by using proximity sensors. Simple contact sensors were used to detect the contact between the part and locator. The fixture design was obtained initially by using the method presented in [3, 5] and the fixture was assembled onto the base plate. This algorithm assumed that the part was initially in three point contact with the support surface. The initial orientation of the part was assumed to be known. The uncertainty in the initial position and orientation of the part and the uncertainty in the commanded velocity of the robot were considered. These uncertainties were eliminated by a translational or a rotational compliance motion which was achieved with a selective compliance mechanism attached to the robot's end effector. The planar motion of the part, caused by the frictional contact between the part and the compliance mechanism during the robot's motion, was monitored by this algorithm. The conditional loading plans were generated based on the status of the contact sensors. Sticking between the part and the locators as well as the unpredictable dynamic snapping of the part (when exceeding the travel limits on the selective compliance mechanism) were observed in practice. The locators were treated as points when, in reality, they were cylindrical in shape. The necessary correction factors to incorporate the locator's dimensions were not considered.

Trappey et al., [22] presented a computer aided fixture positioning method. The method integrated a modular fixture database, a fixture positioning algorithm, a geometric model of the workpiece and a 3-D graphic interface on a CAD/CAM package. The system accepted the boundary representation (BREP) of a workpiece and a set of fixture points of selected fixture elements, called the fixture configuration, as input. Data input options and the modular fixture database were then used to determine the feasible setup of the fixture elements on the base plate. The modular fixture database consisted of the geometrical and topological data of several modular fixturing elements. The fixture configuration was assumed to be found by using existing algorithms that employ the 3-2-1 fixturing principle in a non-modular environment. The spacing between the dowel-pin holes in the base plate was considered to be known, so that the algorithm could enumerate the positions (location and orientation) of the locating pins and the clamps on the base plate. Finally, the appropriate size of the base plate and the appropriate fixture elements were selected from the modular fixture database based on the enumerated set of positional data for fixture elements.

2.1.4 Fixture Evaluation

Zhuang et al., [4] explored the range of applications for two models of modular fixtures. They considered a polygonal part as in [3,5]. The problem was restricted again to planar objects and four point, frictionless contacts. The models involved three locators, one horizontal clamp (3L/1C) and four horizontal clamps (4C). The study revealed that a part which is small enough to fit between four adjacent lattice sites was not fixturable with the 3L/1C model. The authors developed a heuristic procedure to construct a polygonal part of arbitrary size that is not fixturable with the 3L/1C model. Consequently, 3L/1C fixtures are not universally applicable to a set of polygonal parts. The hole type and T-slot type base plates were considered for the 4C model. The study indicated that 4C fixtures always exist for rectilinear parts when all edge lengths are greater than the slot spacing and also for convex polygonal parts with at least three admissible edge segment lengths which are greater than $\sqrt{2}$ times the slot spacing.

Shirinzadeh et al., [10] investigated the performance of the reconfigurable fixturing system reported in [9]. The accuracy and repeatability in locating the fixturing modules on an electromagnetic base plate depended greatly on the accuracy and repeatability of the assembly robot. The experimental techniques needed to measure the accuracy and repeatability of the robot for assembling the fixture modules were discussed. The cycle time to assemble and dismantle the fixture modules was studied and presented.

Hockenberger et al., [18] studied the impact of fixture layout, locator geometry, and clamping force on the displacement of a rigid workpiece during mounting, clamping and milling operations. Two fixture layouts were used to fixture the workpiece based on the 3-2-1 fixturing principle. Inductive displacement transducers were used to measure the translation and rotation of the workpiece with reference to the fixture's reference frame. A pressure gage was used to measure the clamping force of the hydraulic clamps. Results revealed that the performance of a fixture layout can be influenced by the directions of the forces and moments exerted on the workpiece during machining. The results also showed that the locator geometry affected the magnitude of the workpiece's displacement and that flat tipped locators provided better results than spherically tipped ones. The results indicated that a workpiece's displacement, due to deformation at the contact region and slip, was a significant source of orientation error for workpieces restrained over a small contact area.

Penev et al., [21] addressed the problem of incorrectly loading a workpiece onto a fixture and they developed an algorithm for fool proofing the fixturing. Foolproof fixtures permit only one orientation for the loaded workpiece. The algorithm accepted a fixture design, produced by the Brost-Goldberg algorithm [3, 5], and augmented it with fool proof pins that make an incorrect loading impossible. To achieve this goal, the set of all the configurations of a part contacting the three locator positions (obtained from [3, 5]) were enumerated and the desired configuration recommended by [3,5] was eliminated from the resulting set. The remaining configurations represented the undesirable orientations of the part. The minimal set of grid holes that foolproof all the unwanted configurations was then determined iteratively by using a greedy approximation algorithm. The unwanted configurations (involving an incorrect loading) were eliminated by inserting the fool proof pins into the selected set of grid holes.

2.1.5 Conclusions

An extensive literature search of flexible fixture designs indicates that significant research has resulted in a number of contributions. The search shows that most studies have focused on developing fixture design algorithms by using minimal modular fixture tool kits for prismatic workpieces. The workpieces are assumed to be two dimensional and their fixture design has been approached as a planar problem. Most previous research has been confined to a specific, four point contact class to fixture a given polygonal workpiece. The review also reveals that these fixtures are designed specifically for either assembly or inspection operations. The few studies carried out in three dimensional fixturing have considered vertical overhead clamping to prevent the part from lifting off the primary plane. The strategy adopted to directly position the overhead clamps on top of the part poses the problem of collision between the tool and the vertical clamp. The sensor systems developed in some of the studies are either structurally complicated or they are very expensive. It was concluded that none of the reviewed clamping methods are suitable to fixture the parts considered in this study.

2.2 Automated Deburring

The burr and its elimination are a major problem throughout manufacturing industries. Burr removal traditionally employed generic processes such as tumbling, chemical removal, sand blasting and hand deburring. These generic processes do not have the capability to control the point where deburring is required. Automating the deburring process has become a necessity owing to the hazardous nature of the process which, in addition, is labor intensive, time consuming and expensive. The objective here is to eliminate as much manual deburring as possible. The demand for a shorter processing time, without sacrificing quality, and the ability to deburr a wide variety of parts have given rise to the use of robots in automated machining. The tedious task of deburring complex parts can be considered as one of the most appropriate and cost effective applications for unmanned robot machining. A review of the literature pertaining to the field of automated deburring was conducted and the results are presented next.

2.2.1 Review of deburring

Ramachandran et al., [23] reviewed a wide range of literature pertaining to burrs and presented recent progress in burr control, burr removal, and automated deburring. Their report revealed that the formation and properties of machining burrs could be predicted by relatively simple models. Also, automating the deburring process could drastically reduce the component cost and improve the strength, reliability, performance and service life of the product being manufactured. A robot based automated deburring system, introduced by Rolls-Royce in the UK, to deburr cylinder blocks and heads was discussed. The benefits of this system, according to the report, are faster robot programming, a high quality finish without damage to the block and a tolerance of upto +/- 4 mm for an edge deviation. A significant reduction in the cycle time was achieved by using a compliant cutting tool that was designed especially for high speed deburring of complex workpieces.

Seliger et al.,[25] presented an intelligent, sensor integrated, robot for deburring castings. Their system employed a laser scanner to acquire the workpiece's geometry. The laser scanner delivered a formatted data. This system's feed path planning module detected the burrs and automatically generated the robot's feed path. The burrs were detected by matching the laser scanner data with the workpiece's geometrical template. The burr base for each burr was determined as soon as they were detected. A base frame was assigned for each burr base in the robot coordinate system. The tool frame was determined experimentally for the selected tool and the interaction frames were described by using homogenous transformations. This procedure enabled the automatic calculation of the feed path from the burr base and tool interaction frames. The system required a robot controller capable of bi-directional communication with the sensor system. A system to accelerate the processing speed of the burr recognition in order to make it on-line is still under investigation. The software has produced satisfactory simulation results. However, the system has not been implemented.

De-Gol, [26], presented an account of several applications that use a robot and a fixed tool / moving workpiece concept. According to the author, such a system resulted in an economic and simple installation by using a robot for both positioning and orienting of the workpiece. The reported applications included the automatic glazing of automobiles, roller seam welding of fuel tanks and car wheel housings, deburring and grinding cast tracks for military vehicles, the transfer of formed panels between power presses, spot welding and arc welding.

Cole, [27], presented a brief report on the performance of three dimensional abrasives. It was observed that the scotch-brite brand products of 3M abrasives were able to remove microscopic surface burrs. These abrasives were also very conformable so that they did not damage metal surfaces by removing excessive surface material or by scratching the surface. Also, these abrasives can automatically generate rounded edges, with the radius ranging between 0.002" to 0.005".

2.2.2 Conclusion

The literature search indicates that only a few papers have been published in the field of automated deburring. Most papers are published by abrasive tool manufacturers. These papers depict the various applications that utilize the manufacturer's products for deburring and surface finishing. Few researchers have focused on sensor integration for on-line burr tracking while deburring. Although the concept of sensor aided systems has been demonstrated by using simulations, such a system has not been implemented in practice. Reports on automatic robot path generation asserted the feasibility but the practical implementation is still to be explored.

Chapter-3 Burrs and Deburring

3.1 Introduction

The mechanism of burr formation is complex. With three dimensional plastic deformation and a high degree of freedom, a theoretical analysis is very complicated. Thus, only a few papers have been presented that deal with the basic mechanism of burr formation in machining [23]. Burrs can be classified into four basic types based on the mechanism of their formation. They are listed next.

1] **Poisson burr:** Formed as a result of the tendency of the material to bulge at the sides when compressed until permanent plastic deformation occurs.

2] **Roll-over burr:** Formed when the material or chip is pushed out of the cutter's path rather than sheared. This type of burr is normally the longest burr found at the end of machining.

3] **Tear burr:** Formed as a result of the material tearing loose from the workpiece rather than being sheared. This type of burr occurs mostly in punching.

4] **Cut-off burr:** Formed as a result of the separation of the workpiece from the raw material before the separation cut is finished. This type of burr occurs mostly in saw cutting.

The above types of burr can occur separately or as a combination, depending upon the nature of the operations performed on the workpiece. In general, a burr can be related to any of the following conditions that result from the various operations performed on metal.

- A rough or sharp edge that is left on a part by a cutting tool.
- A jagged edge that happens around a punched hole.

- A small amount of material that extends from the edge of a hole as the result of drilling.
- A fragment of excess material or foreign particle that adhers to the surface of a machined part.
- A rough or sharp ridge that remains on a part's surface after machining.
- An undesired displacement of metal that occurs at the intersection of surfaces.

The best way to eliminate a burr when machining is to replace the work material with one that is less ductile. However this method is not practical in most cases. Even with a less ductile material, the total prevention of a burr is almost impossible. This necessitates the need to device a method to remove the burr. Burrs occur in varying sizes and the cost of burr removal is proportional to the size of the burr [23].

3.2 Effects of burr

Precision machined parts or components should be free of burrs under ideal machining conditions. However, in practice, production demands, machining conditions and dull cutting tools result in the formation of an undesirable burr which affects the quality of the precision part. The presence of the burr may lead to one or several of the following situations.

- Cut hands while handling parts.
- Jamming mechanisms.
- Interference and scoring of mating parts.
- Increased friction and wear on mating parts.
- Cut wires resulting in short circuits.
- An induced stress concentration.

- An induced stress cracking.
- Impairment of the functionality of the part.
- Poor product finish, appearance and quality.

3.3 Deburring process

Deburring can be defined as the operation of peening or removing burrs to eliminate an edge's sharpness. The generally adopted method of burr removal is manual deburring. This method is mostly employed in situations where consistency on parts of high complexity or a high tolerance is required. Also, there are several other reasons for employing manual deburring. A few of these reasons are listed below.

- The parts have complicated shapes.
- It is difficult to reach the burr.
- The parts have a close tolerance.
- The parts are delicate.
- The batch size is small.
- Large edge radii are required.

Although the manual operation is slow, costly and tedious, many parts in the aerospace and automotive industries are deburred manually because more appropriate automated alternatives are not available. The quality of the edges produced manually cannot be defined perfectly. Industries may have developed certain standards for the finished edges and surfaces, that are specific to their products , but no published data exists on these standards. Hence, the problem of hand deburring has not been solved completely. The large costs associated with manual deburring necessitates the implementation of a well defined process.

Although the term "deburring" limits itself to the context of burr removal, there is still more to deburring than just burr removal. The deburring process can be related to all the secondary operations that are required to finish a part completely. In this study, the various manual deburring operations of the Boeing-777 parts are classified broadly into three categories in order to facilitate the definition and implementation of the appropriate deburring processes. These categories are discussed in the following sections.

3.3.1 Edge deburring and chamfering

The Boeing-777 parts undergo a liquid penetration inspection immediately following the initial machining in order to check for the presence of any surface cracks. The parts also undergo a dimensional inspection on a coordinate measuring machine. A representative sample of the parts considered in this study is shown in Figure 3.1. The flanges and cross ribs (which are labeled in Figure 3.1) may possess sharp edges along with burrs. The burrs, as well as sharp edges, need to be deburred initially to enable safe handling of the parts during their inspection. Also, all the edges are required to be rounded to a radius within 0.020" to 0.040". Certain deburring tools, when operated on a sharp edge with a very low feed rate, can produce this roundness but the procedure results in a long deburring time. The objective here is to minimize the total deburring time. The majority of the material can be removed by using a hard deburring tool on all the edges. This process produces a uniform chamfer. This necessitates the need for chamfering on all the edges prior to the rounding operation in order to expedite the deburring process. As the edge deburring and chamfering operations can be performed by the same tool, these two operations can be combined advantageously into a single operation by using the appropriate tool.

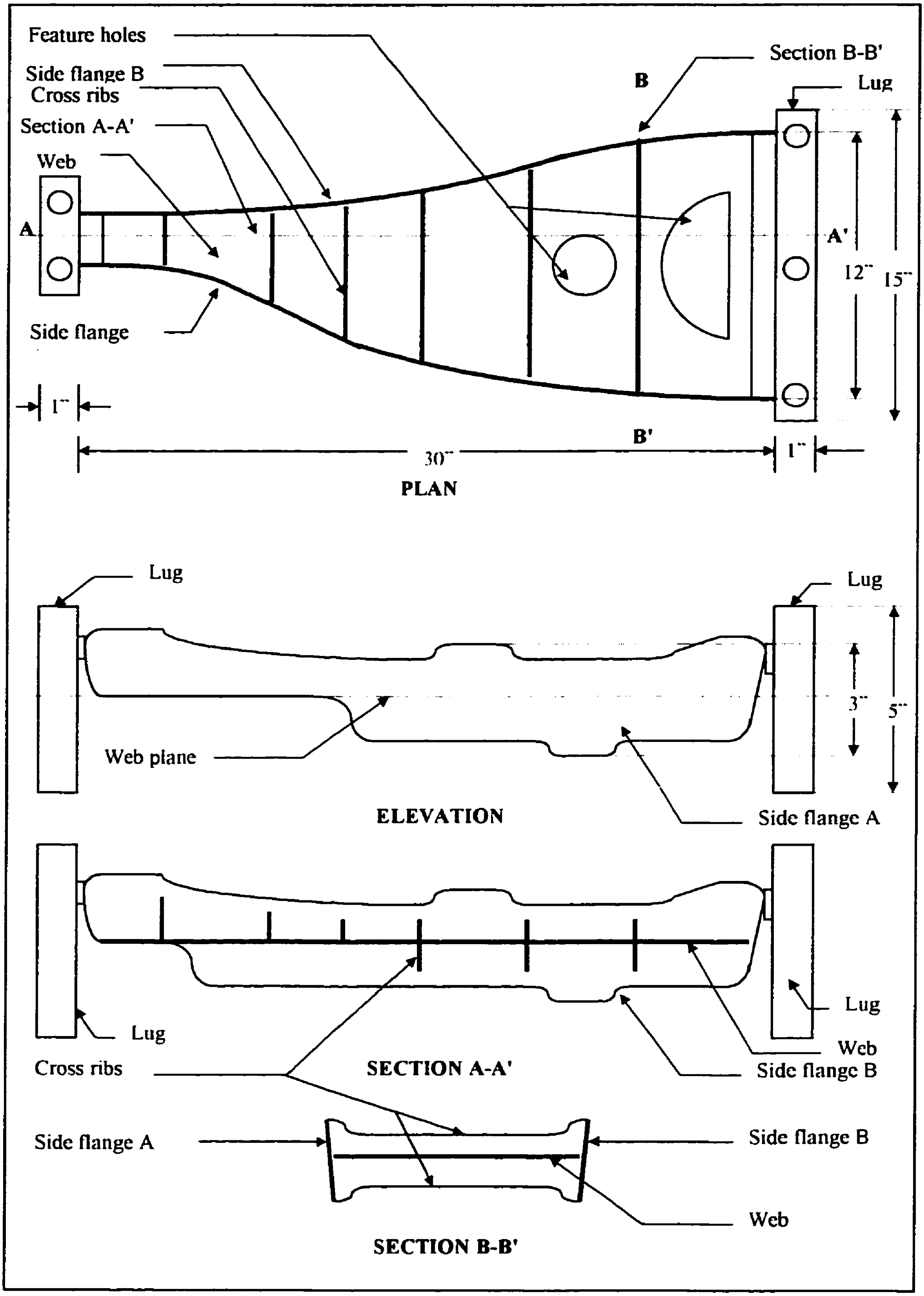


Figure 3.1: Representative part

3.3.2 Edge rounding

Assembled aircraft components are often subjected to high stress levels and vibrations during operation. Sharp edges tend to crack under these conditions. The creation of rounded edges in such parts is necessary to prevent stress cracking and failure. Also, parts that require residual stress removal undergo shotpeening. During shotpeening, any sharp edge present in the part will tend to "roll over" which results in a new burr. Thus, a uniform radius on the edges can substantially improve the thermal and mechanical fatigue strength of such highly stressed components. The radius requirement of 0.020" to 0.040" on the Boeing-777 parts is often termed the "sonic radius".

3.3.3 Surface blending

BAL requires that the surfaces of all the Boeing-777 parts should be blended to a roughness of within 125 microinches. A surface mismatch is a condition caused by small inaccuracies in the depth of cut between two adjacent tool paths whilst roughing the part's surface. This results in several strips of surface planes with sharp edges that are at different heights on the same surface. BAL requires that this mismatch should be within 0.010" and the sharpness of the strip's edges should be removed. Also, the surface waviness and tool marks on the part's surface should be eliminated.

3.4 Deburring tools

The performance in deburring depends, to a large extent, on the performance of the different deburring tools used. A large variety of deburring tools are available commercially. Information pertaining to the characteristics and performance of these tools has not been published. Hence, the need to evaluate and select appropriate deburring tools has paramount importance.

A FANUC-S12, articulated robot with six degrees of freedom and a payload capacity of 25lbs was made available for the present study. The robot was equipped with a quick tool changing mechanism to expedite a tool change between successive deburring operations. Scrapped Boeing-777 parts and detached lugs were used as coupons to conduct the edge deburring and surface blending experiments. Trials were carried out with several deburring tools to produce a uniform and acceptable finish on the coupons. The FANUC-S12 robot was used to transport the deburring tools. Also, light air motors were used to operate the various deburring tools. The air motors were operated at an approximately 90 psi input air pressure. The FANUC-S12 manipulator, together with the end effector, is extremely rigid when the robot is energized. Hence, the deburring tools are deprived of a compliant motion along a tool's axial and radial directions. Deburring a part's edge or surface by rigidly holding the tool against it may lead to excessive material removal, the tool gouging the part, excessive heat generation and faster tool wear. Hence, the rigidity of the manipulator poses a major setback in using abrasive tools on aluminum parts. Also, the robot's rigidity imposes certain restrictions on the selection of an appropriate abrasive tool for deburring the edges and surfaces of aluminum parts.

Several types of deburring tools, such as files and a hand operated sanding belt, are presently used manually to deburr the Boeing-777 parts. The objective here is to minimize the number of different tools used to deburr the parts and form a standard set of tools. The deburring processes mentioned earlier can be defined for all the parts with a standard set of deburring tools. Abrasive tools are made by bonding abrasive minerals (such as aluminum oxide, silicon carbide, ceramic aluminum oxide, alumina zirconia or industrial diamonds) into a desired shape. The size of the mineral used in a given tool determines the grit size of that tool. The density of the mineral in the bonding media determines the percentage loading of the tool. Deburring tools can be classified broadly into three categories in order to facilitate the selection of the appropriate tool for a given deburring process. These categories are: (i) cylindrical tools, (ii) flat circular tools, and (iii) string brushes. The performances of these categories are discussed in the following sections.

3.4.1 Cylindrical tools

A cylindrical tool, which is illustrated in Figure 3.2, has an abrasive surface parallel to the axis of rotation. Hence, the direction of the abrasive action is perpendicular to the axis of rotation. Such tools are available in different grades such as coarse, medium, fine and very fine. The grades are determined based on the size and density of the abrasive minerals. Higher grade tools are very abrasive and tend to gouge the material when used on the edges of an aluminum workpiece. As these harder tools are less forgiving, failure to use them without a proper compliance assistance may result in irrecoverable damage. Lower grade tools are less abrasive and they conform to edge profiles. The resulting deformation of the tool's abrasive surface is shown in Figure 3.2. As these tools conform to the edges, they produce smooth rounded edges with radii less than 0.005" rather than a chamfering of the edges.

Deburring sharp edges with medium or fine grade cylindrical tools will result in the formation of a deep groove along the tool's abrasive surface. A radial compliance should be provided, therefore, to the deburring tool to ensure a constant pressure between the deburring tool and a part's edge. Compliance can be provided by employing a constant force device. The compliant motion provided by such devices is unidirectional with a linear travel that ranges between -0.5" to +0.5". This travel limitation restricts the tool from approaching a part's edge from any desired direction. This restriction also makes the task of programming a robot more complicated. The tool deformation and wear, in the absence of a lateral compliance, will eventually lead to a loss of contact force between the tool and the edge. Hence, the initial part of the deburring cycle produces a well deburred edge and the later part produces a poorly deburred edge. Axial compliance will not have any effect on the performance of the lateral surface of the cylindrical tool. The bottom surface of these tools, as shown in Figure 3.2, can also be utilized to deburr the surfaces as well as the edges of a part. They produce well rounded edges of radii less than 0.005". An axial compliance will have a significant effect on the performance of the bottom surface of the cylindrical tools. Also, an increased dwell time of the tool on the edge or surface affects the tool's performance which increases the material removal but with greater heat generated and more tool wear. A prolonged dwell time inflicts a thermal stress on the part.

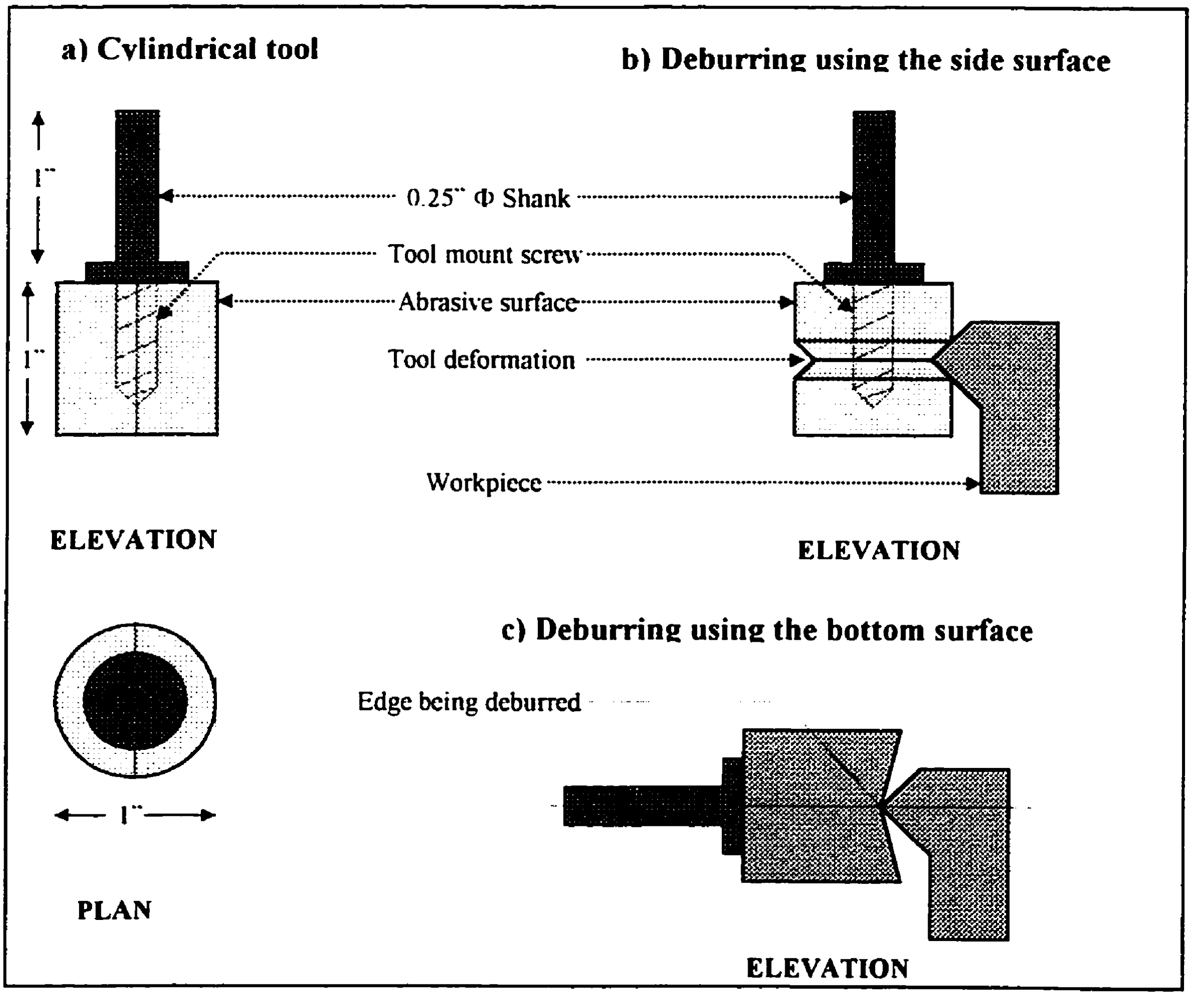


Figure 3.2: Cylindrical abrasive tool

3.4.2 Circular disc tools

A typical circular disc tool is shown in Figure 3.3. Such tools are generally between 2" to 3" in diameter and they are about 0.25" thick. Circular discs have their abrasive surface oriented perpendicular to the axis of rotation. These tools are available in three grades namely coarse, medium and fine. They are stiff and do not conform to curves. Hence, they produce a chamfer on an edge. These flat tools are most suitable for deburring and blending surfaces. The aluminum dust generated whilst deburring tends to clog the microscopic space between the abrasive minerals in the tool which eventually affects the tool's performance. The practice of operating flat tools with a 3 to 5 degrees tilt is found to substantially reduce tool choking. Even though the wear in the tool is slow and even, it will lead eventually to a reduction in the contact force between the tool and the part's surface. This situation can be prevented by employing a compliant device that can tolerate tool wear offsets and yet maintain the contact force on the surface.

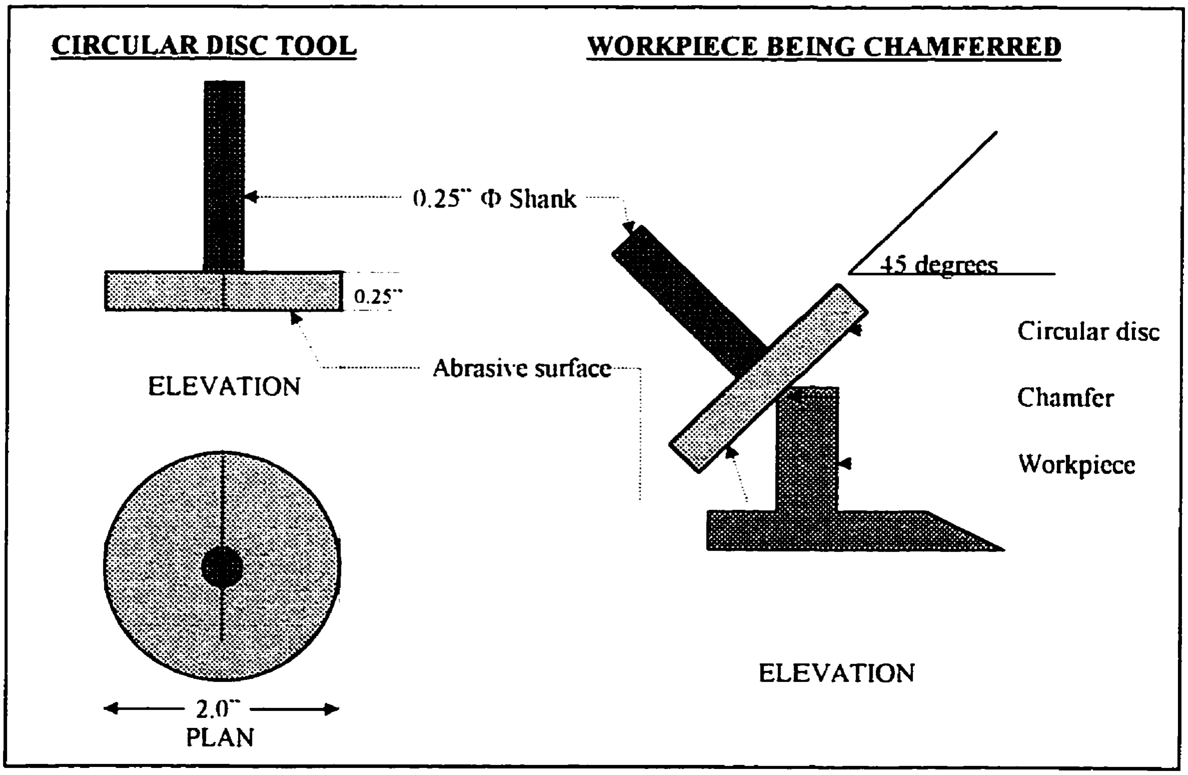


Figure 3.3: Circular disc abrasive tool

3.4.3 Constant force device

Abrasive tools deburr due to the force they exert on a part. In order to obtain a uniform finish, it is important to maintain a constant force throughout the deburring. Robots are generally structurally stiff when they are energized. However, a small compliance is introduced at the end of the robot's arm by the tool. If the compliance is not maintained at a constant level, it becomes difficult to accurately track complex edges and surfaces. Therefore very careful programming and many taught points are required so that the robot can accurately follow contours. However, a constant force device, like the one shown in Figure 3.4, can considerably simplify the programming by reducing the number of taught points and also by decreasing the precision necessary for the remaining points. Also, these force devices practically eliminate the frequent and tedious task of programming the robot for offsets to compensate tool wear. Constant force devices can tolerate inaccuracies and they are more forgiving by providing an axial compliance to the tool when it encounters misaligned surfaces. This feature further simplifies the programming task.

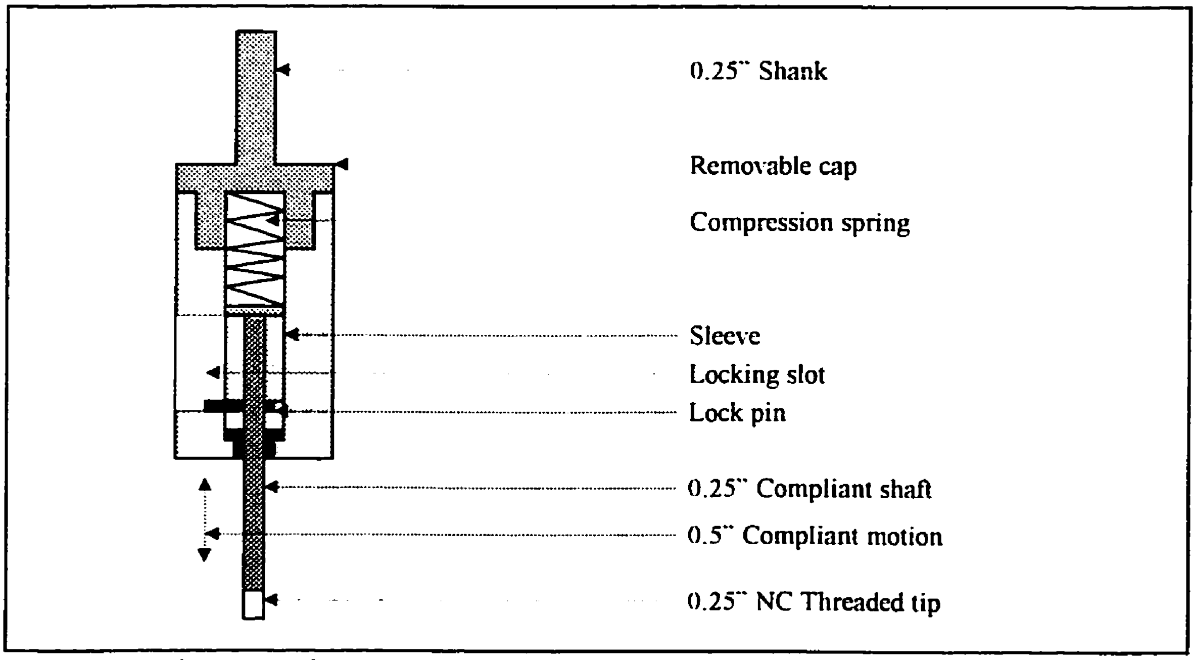


Figure 3.4: Constant force device

In the case of deburring, a constant force device can be attached to the air motor's collet. This device is equipped with a spring loaded shaft which can slide freely 0.5" into its housing. The relative rotary motion of this shaft, with respect to its housing, is restricted by means of a locking pin. The constant force device is precision machined to avoid any play between the shaft and housing. The free end of the shaft is provided with a 0.25" NC thread to accomodate various deburring tools. The constant force device ensures a positive contact force while deburring. This contact force may range between 0.1 lb to 10 lb depending on the displacement of the shaft inside its housing as well as the spring constant. The constant force device compensates for disc wear as well as slight programming and positional variations. Consequently, parts can be deburred with greater uniformity.

3.4.4 String brushes

String brushes are made of nylon filaments that are impregnated with abrasive minerals such as silicon carbide or aluminum oxide. The nylon filaments are arranged radially about a central hub. They may have either a round cross section or a rectangular cross section. Also, the filaments can be either straight or wavy. Each filament acts as an individual flexible file that abrades metal with their tip as well as their sides. The filaments are very compliant and they can reach complex portions of a part which may not be achievable with a cylindrical or a flat tool. The string brush conforms very well to edges and can efficiently round sharp edges with radii upto 0.015". However, a sharp edge should be processed in two stages with the string brush, as shown in Figure 3.5, in order to obtain a perfectly rounded edge. The size of the radius produced is proportional to the dwell time of the brush on the edge. For larger radius requirements, the dwell time can be increased by decreasing the feed rate. One alternative approach to obtain a larger radius is to chamfer the edges prior to the rounding operation. The filaments become stiff at very high motor rpm, losing their compliance. This results, in turn, in damage to the filament.

Also, an increased dwell time generates more heat which might affect the performance of the nylon filaments.

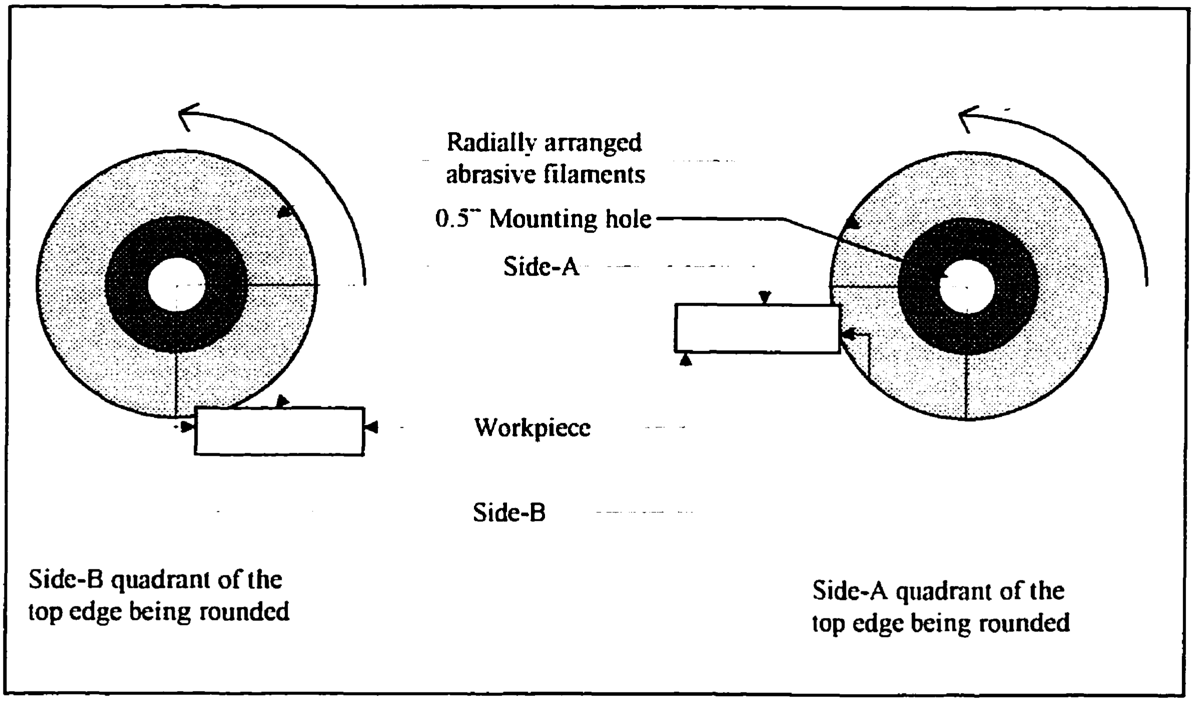


Figure 3.5: String brush

3.5 Commercial tools

3.5.1 Edge deburring and chamfering

Surface Conditioning Discs: Surface conditioning discs feature an abrasive impregnated, web construction. These discs conform to small edge variations and are commercially available in four different hardnesses namely, soft, fine, medium and coarse. A coarse disc produces a smooth chamfer when used on a part's edge. All the other discs deburr but do not produce the desired chamfer. These discs are good on surface conditioning applications. The web construction drastically reduces the disc life when used on sharp edges. The discs wear quickly and break when they are used to chamfer sharp and complex shaped edges.

Unitized Wheels: Unitized wheels are strong and efficient in edge deburring and finishing. They are commercially available in six different hardnesses namely, 8A-coarse, 8A-medium, 6A-medium, 6A-soft, 2A-medium and 2A-soft. Preliminary experiments were performed on coupons by using all these hardnesses. The results revealed that the 8A-coarse unitized wheel produced the desired chamfer at a feed speed of 40 mm/s. Increasing the feed speed will reduce the processing time as well as the chamfer size. The major problem faced in using these tools is the deburring and chamfering of a part's curved edges. Curved edges cannot be approached by the flat surface of the tool. However, the tool can be used sideways to deburr curved edges. There is no compliance in the tool along its circumference and, hence, this tool is very aggressive along its lateral surface. This results in over gouging at the line of contact. Also, the tool wears quickly along its circumference which results in a loss of contact between the tool and the curved edge at a later stage of deburring. A unitized wheel softer than 8A coarse needs to be used to deburr curved edges.

Bristle Discs: Bristle discs perform well on general surface conditioning applications such as, rust and paint removal. They are commercially available in three different hardnesses namely, soft (120 grit), medium (80 grit) and hard (50 grit). These discs grind adjacent surfaces, more than deburring and rounding the edge, when used on a part's edge. Hence, the results obtained are unsatisfactory.

String Brushes: String brushes are very compliant and they produce rounded edges very well. These brushes produce radii of upto 0.015" when used on a sharp edge at a 30mm/s feed speed. On the other hand, these brushes produce radii of upto 0.040" when used on a chamfered edge at a feed speed of 30mm/s. Increaing the feed speed, again, will reduce the processing time as well as the edge's radius. The interference of the strings with the edge plays a major role in the rounding operation. Preliminary trial results revealed that an interference of upto 2mm with a 120 grit string brush is sufficient to generate the desired radii of upto 0.040". The string brush just grinds the surfaces adjacent to the edge and it leaves the edge without rounding if the interference is greater than 2mm.

Fladder: Fladders are thin, circular, radially stripped, abrasive coated cloth. They are very compliant and they produce rounded edges very well. They operate at a very low speed of 900rpm. Fladders require an interference of 1" to generate a rounded edge. They also grind the surfaces adjacent to the edge being rounded. As deburring is carried out before the LPI inspection, the use of fladders may affect the LPI result. Also, it takes a longer time to deburr and radius the edges by using a fladder.

3.5.2 Surface finishing

Unitized Wheels: A 2A-medium grade, unitized wheel produces a polished surface. This tool leaves tool ridges and surface mismatches untouched. A 6A-medium grade, unitized wheel produces a uniform surface that is free of burrs and ridges. It also reduces the surface mismatches to an acceptable level. Surface finishing is a slow process and results in a finished surface roughness of 65 microinches. The tool leaves circular marks on the surface if operated at feed speeds greater than 5mm/s. A 8A grade tool is very coarse and leaves a rougher surface. The 8A grade tool also results in an undesirable reduction of the part's thickness.

PG Wheels: PG wheels perform very well on ridges and surface mismatches. They leave a score mark on the finished surface. The problem associated with this type of tool, when used in robotic applications, is that it is not possible for the end effector to approach the part's surfaces without hitting the part's flanges.

3.6 Conclusions

Extensive preliminary experiments were carried out at Bristol's premises to select appropriate tools for robotic deburring, edge rounding and surface blending of aluminum parts. The trials were perofrmed on aluminum coupons. The experimental results revealed the following. The 6A-medium unitized wheel produced the desired surface roughness of 65 microinches which is substantially lesser than the maximum limit of 120 microinches. However, the operation was slower, relative to other operations, with a feed speed of 5mm/s. The processing time can be improved by increasing the feed speed but the resulting surface finish has to be compromised. The 8A-coarse, unitized wheel produced the desired results for edge deburring and chamfering. Curved edges can be deburred with the 2A-medium or 6A-medium, unitized wheels. The 120 grit string brush produced the desired radius of less than 0.040" at a 25mm/s feed speed.

Chapter-4 Automated Fixture System

4.1 Introduction

The requirement that fixtures invariably provide a precise location and a rigid support of the workpiece has always been the basic principle of fixture design. Generally, an object in space can be related to a datum (X, Y, Z) reference frame which is defined by three mutually perpendicular datum planes. It will have twelve degrees of freedom that correspond to translational and rotational movements along the positive and negative X, Y and Z axes. The objective of fixturing is to restrain a workpiece from all these movements. Fixture design for prismatic workpieces can be classified into two major categories, namely the supporting and locating category and the clamping category. The principle of the supporting and locating category is to employ supporters and locators to restrict the maximum number of movements. The principle of clamping is to use horizontal and vertical clamps to restrict the remaining movements. Typically, supporters and locators restrict at least nine movements with the remaining three movements constrained by clamps.

Fixturing techniques for non-prismatic workpieces often depend on the workpiece's shape. There are no generalized fixture design principles for non-prismatic workpieces because of the complex nature of the workpiece's geometry. Fixture design also depends on the nature of the operation to be performed on the workpiece. Conventional fixtures such as vises, chucks and toe clamps are good only for simple prismatic workpieces. For complex as well as delicate parts, the fixturing device will have to be a custom designed one that often only works for that part. The capacity of the fixture to handle different part shapes is a measure of its reconfigurability. Although reconfigurability is a key requirement for automated fixturing, it should not be at the expense of reliability, precision and rigidity when dealing with a part family that comprise parts having different sizes and geometries. Modular tooling sets are used extensively in industry and they represent the state of the art in fixturing. The use of such sets can speed the design and construction of fixtures for small batch sizes. The sets can also reduce the cost of storing a variety of fixtures that may be required in a typical production environment. The fixture setups for any given part can be replicated rapidly, providing an efficient method of recording the settings can be evolved. The tool set components should be precision machined in order to achieve sufficient precision in the assembled tool.

As stated earlier, the challenge of this work is to develop an automated system that is capable of fixturing the 40 different BOEING-777 parts during edge deburring and surface finishing. A FANUC-S12, six degrees of freedom, articulated robot was available for the deburring operations prior to developing the fixture design. The parts experience low cutting forces, ranging from 0.5 lbf to 3 lbf, during duburring. As deburring is carried out with the aid of an articulated robot, the entire top surface of the fixtured part should be made accessible for the robot to perform these operations. This provision prevents any possible interference from the fixture components in the robot end-effector's path. The use of vertical clamps interferes with the end-effector while processing the workpiece and such clamps should be avoided. The fixturing methodology should also be applicable to other machining applications that involve low cutting forces. The design should permit the robot to assemble and load the fixture in order to perform unattended processing. Furthermore, the fixture system should be controllable by a programmable device.

4.2 Proposed fixture system

The concept of modularity is adopted here. The new fixturing system comprises custom designed components to meet the fixturing as well as the processing requirements for the part family considered. These components are also designed to enhance the system's modularity, sensory feedback capability and programmability. The new system forms part of a robotic deburring cell, as shown in Figure 4.1. It comprises a FANUC-S12 robot, a five station tool rack and the modular fixture system. The FANUC-S12 robot is equipped with a tool changing mechanism in order to expedite the tool changeover between successive deburring operations performed on any given part. The fixture system comprises a base plate, sensor integrated, horizontal locators, horizontal pneumatic clamps, vertical supporter modules, vacuum pumps and a programmable logic controller. The design and function of the fixture components are discussed in the following sections.

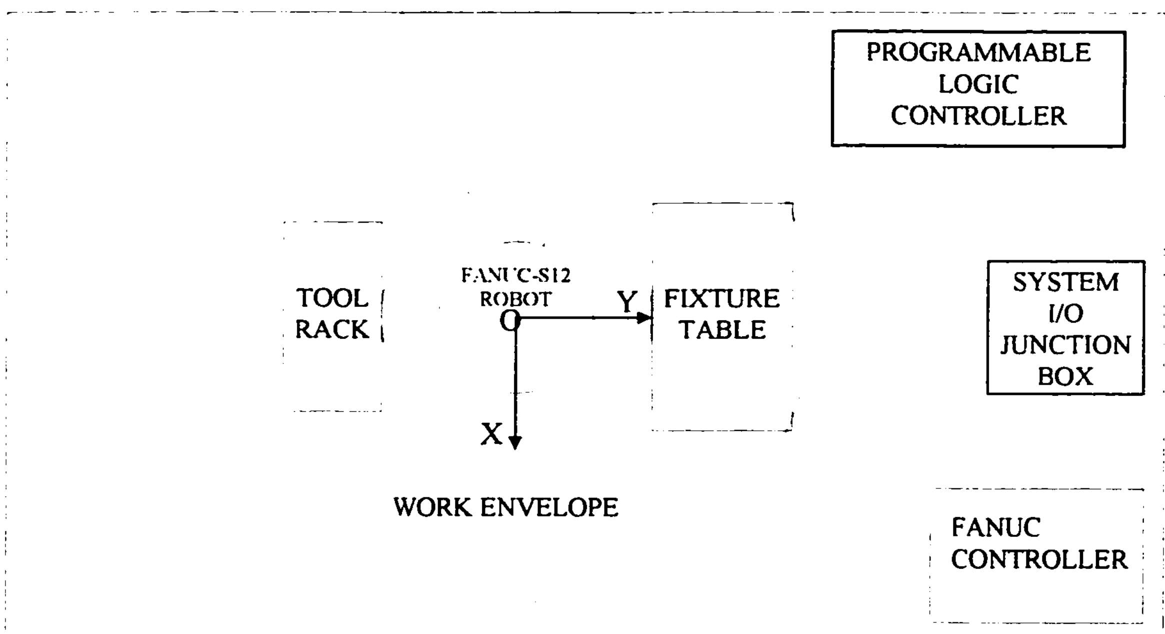


Figure 4.1: Robotic deburring cell

Three base plates are mounted adjacent to each other on a steel frame to form a 60" x 20" fixture table, as shown in Figure 4.1. The steel frame is attached firmly to the floor to add rigidity. The base plates are leveled precisely to provide the primary (X-Y) reference plane. The supporter modules (detailed in section 4.2.2) provide vertical support and stability to the workpiece. The supporters are equipped with vacuum suction cups so that they can also constrain the workpiece vertically. Also, the supporter modules provide a clearance between the fixture table and the workpiece to enable interference free, deburring operations. The supporter units are machined precisely and they can be latched rigidly onto the fixture table. The horizontal locators (which are detailed in section 4.2.3) provide the secondary and tertiary reference planes in order to locate the workpiece positively on the fixture. These locators also provide a feedback signal to the programable logic controller (PLC) when they establish contact with the workpiece in order to ensure the proper placement of the workpiece on the fixture. The horizontal clamps are employed to constrain the workpiece in the horizontal plane. The fixture system has two horizontal clamps to constrain the workpiece in the secondary and tertiary planes, respectively.

4.2.1 Base-plate

The base plate is a 20" x 20" x 1.2" steel plate purchased from a supplier. It contains a lattice of dowel and tapped holes that are arranged alternatively, as shown in Figure 4.2. The dowel holes are 0.5" in diameter and they are machined precisely. The tapped holes are provided with 0.5" X 24 NC thread. These holes are spaced apart precisely at 1.25" with tolerances of the order of +/-0.005". The holes are used for locating and fastening the fixture components. The top surface of the base plate is ground precisely to a flatness of +/-0.001". The base plate is also equipped with 5/8" dowel holes and countersunk bolt holes in order to precisely locate and fasten the base plate onto the steel frame.

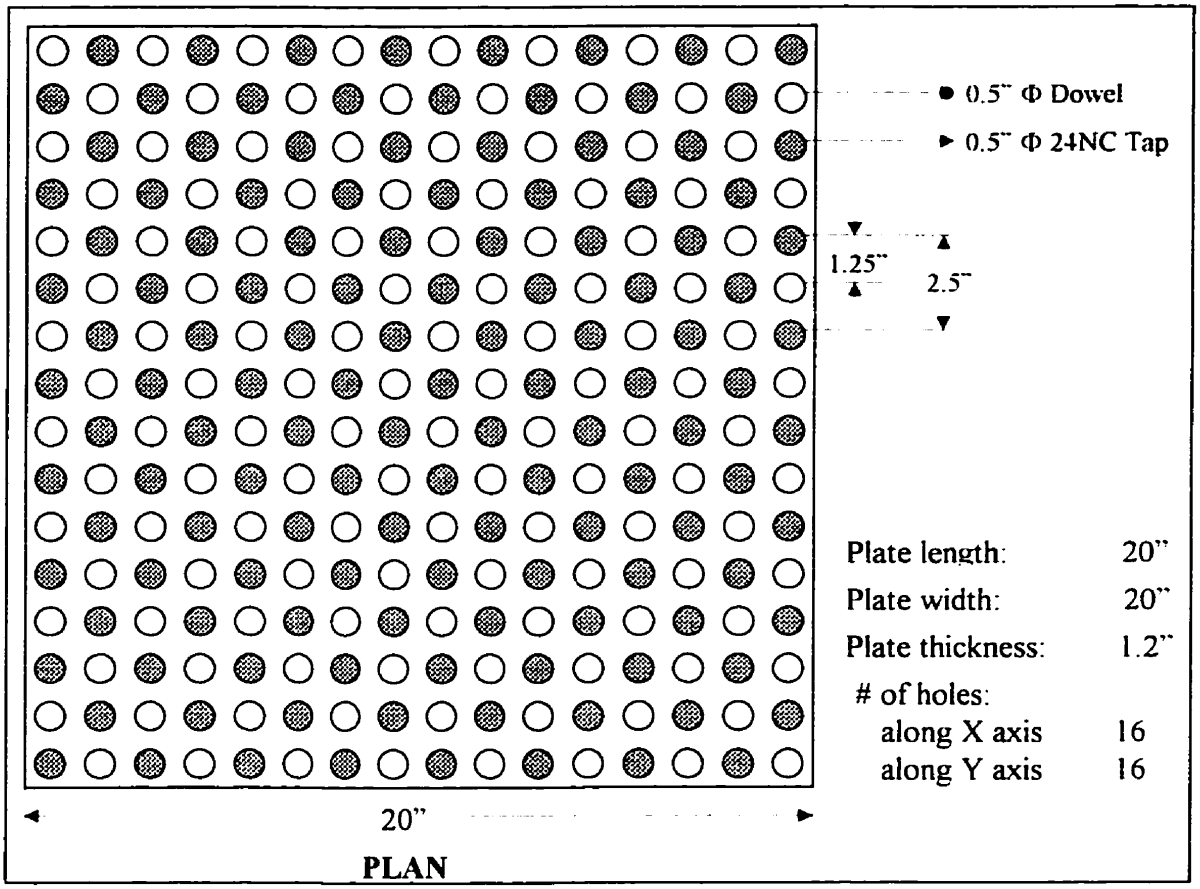


Figure 4.2: Base plate

The benefits of using the dowel type base plate are summarized below.

1) The fixture components can be mounted on the base plate by merely inserting them into the selected dowel holes. This process enables the loading and unloading of the fixture components to be performed by a robot. It also enables a quick changing of fixture's configuration.

2) A reference frame can be defined for the base plate so that the programs controlling the robot's motion can be developed with respect to this reference frame. Thus, a flexible transfer of the motion programs is possible between cells employing compatible robots and identical fixture system. The reference frame also enables the processing of several identical parts held on several identical fixtures, in the same cell, with a single set of motion programs and corresponding frame shift parameters.

3) The fixture components can be located accurately and repeatedly on the base plate for any given fixture configuration. Their coordinates, with respect to the base plate's reference frame, will remain intact even after several changes of the fixture's configuration.

4.2.2 Supporter module

The custom designed supporter module provides the support function as well as the vertical clamping function from underneath the part that is to be fixtured. The supporter module also provides sufficient clearance between the part and base plate. This last feature enables the deburring tools to freely perform their operations without running into the base plate. After examining the geometry of candidate parts, it was determined that at least three supporters are required to provide adequate support from underneath the part. The support points are selected to be in the same horizontal plane and spaced as far apart as possible on a machined surface to ensure maximum stability and a uniform weight distribution. However, it may be required to provide additional supports to prevent the part deflecting during deburring. Vertical clamping is achieved by vacuum suction. The suction prevents the part from getting dislodged by firmly anchoring it to the supporter with adequate force to overcome the light deburring forces.

The supporter module consists of a supporter unit and a supporter clamping unit, as shown in Figure 4.3. The supporter unit comprises a support stem and a vacuum suction cup. The support stem is equipped with (i) a threaded top to mount the vacuum suction cup, (ii) a collar to ensure proper seating on the base plate, (iii) a through hole along the stem's longitudinal axis to transfer the vacuum from the nozzle to the suction cup, (iv) a dowel insert to enable free insertion as well as play free assembly, (v) an O-ring seal to prevent any possible vacuum leak between the stem and the nozzle, and (vi) a locking groove to anchor the stem to the base plate. The vacuum suction cup (PIAB-U50-

SIL-50 model), purchased from a supplier, has an external rim diameter of 2.09". It can provide a lifting force of 16.4 lbf at -18" Hg of vacuum supply. The vacuum pump (PIAB-L10 model) that supplies the vacuum can produce -19.5" Hg of vacuum at 87 psi supply pressure.

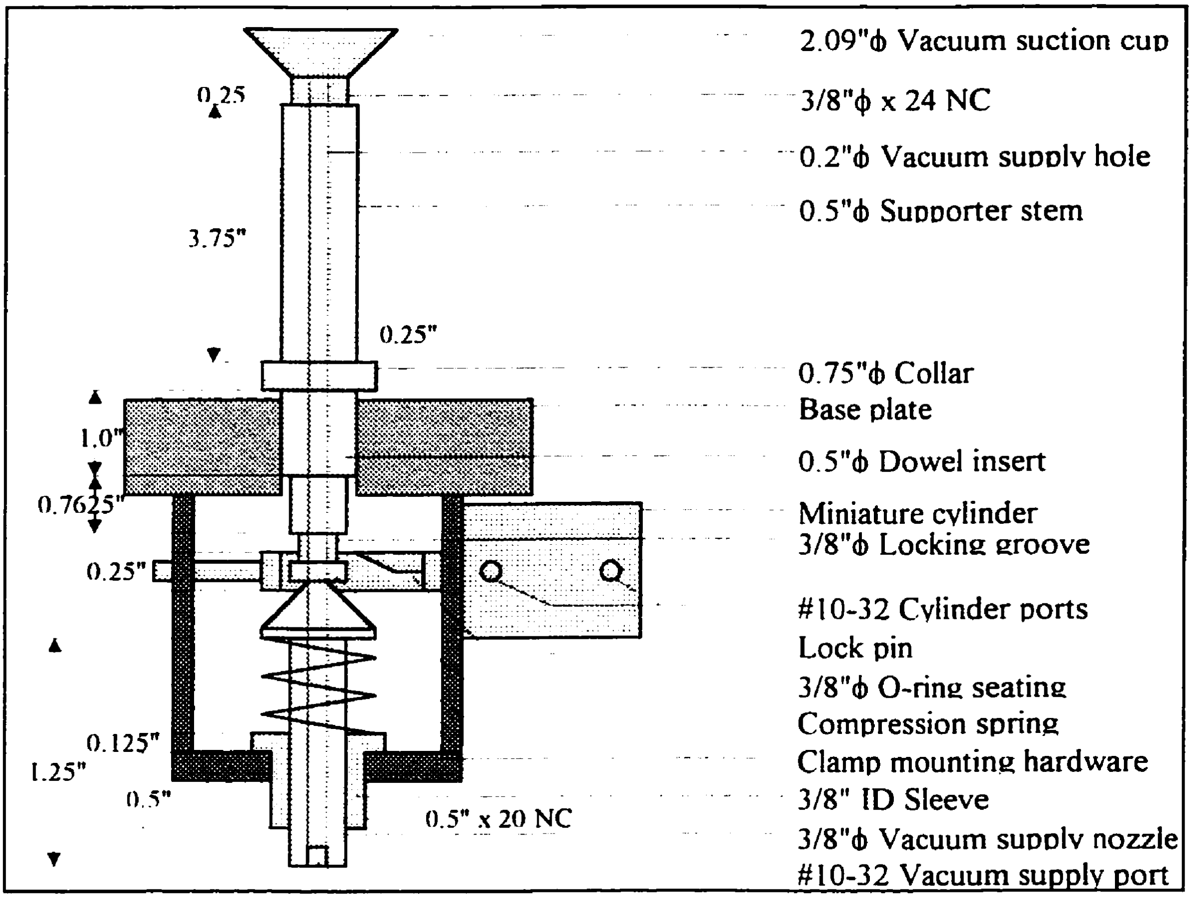


Figure 4.3: Supporter module

Each supporter mounting hole on the base plate is equipped with the supporter clamping unit, as shown in Figure 4.3. The supporter clamping unit is designed to provide two functions, namely firmly anchoring the support stem to the base plate and establishing the connection between the nozzle and the support stem. The nozzle is held against the O-ring seal at the bottom of the support stem by a compression spring. The clamping mechanism comprises a miniature double acting cylinder with a 1/2" travel, a lock pin and the mounting hardware. The cylinder is actuated by a miniature 110 VAC solenoid valve.

The supporter module was custom designed. All the components are machined at BAL's tool build facility. The dimensions given in Figure 4.3 have a +/-0.001" tolerance.

4.2.3 Horizontal locator

The horizontal locator is custom designed to provide three functions namely: (i) precisely locating the workpiece in a given location, (ii) restraining the part's motions, and (iii) detecting the presence as well as the proper placement of the part on the fixture table. Provisions for locating sensors is also considered in the design. The sensor provides a feedback in detecting the presence of the locator to ensure the proper insertion of the locator into the dowel hole in the base plate. The locator is designed to function as a normally open switch that closes when a part contacts the locator. The horizontal locator has three components namely, the upper stem with flange, the lower dowel insert with flange and a contact pin. See Figure 4.4.

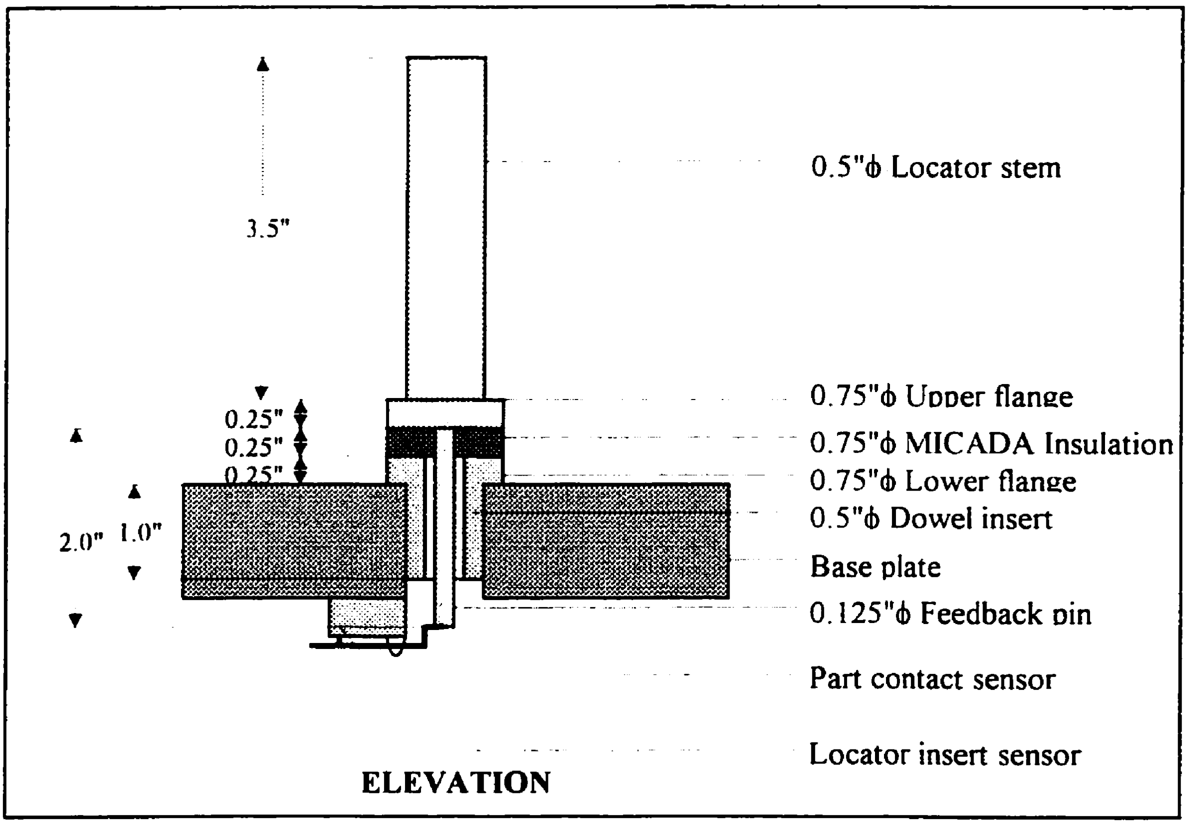


Figure 4.4: Horizontal locator

A 0.25" thick insulator (micada) is sandwiched between the two flanges with an epoxy which is cured for four hours at $250^0 C$. Once cured, the epoxy can resist shear forces upto 3000 lbf. The contact pin extends the electrical continuity from the locator stem to the bottom side of the base plate in order to avoid lead wires on top of the base plate. A contact sensor, which is attached to the bottom side of the base plate, assists the detection of a contact between the workpiece and locator. Moreover, it confirms the workpiece's location on the fixture. The pin also actuates a limit switch (attached to the bottom side of the base plate) when the locator is inserted into the dowel hole. This limit switch assists in detecting the presence of the locator unit in the appropriate dowel hole. Maximum fixture stability is achieved by positioning locators as far apart as possible.

4.2.4 Horizontal clamp

The horizontal clamp, which is shown in Figure 4.5, is designed to provide a point fixture contact to the workpiece. It also provides adequate clearance for the deburring tools to perform without running into the clamps. Dowel pin mounting has been adopted to enable the robot itself to assemble these clamps on the base plate.

The horizontal clamp consists of a 1/2" diameter contact, end pin, a double acting cylinder with a 3" travel, a clamp base, two guide rods, four linear bearings and a mounting block with two dowel pins spaced 2.5" apart. The clamp base houses all the clamp components. The contact end pin is actuated by the cylinder which is attached to the base plate. The guide rods prevent the rotation and deflection of the contact end pin by ensuring a linear motion while clamping. The linear bearings provide a friction free clamping action. The contact pin is equipped with a rubber sleeve in order to avoid damaging the part while clamping. The mounting block is equipped with two dowel pins to prevent the clamp from rotating on the base plate. The dowel pins are spaced 2.5" +/- 0.001" apart. The clamp can be employed either along the length or width of the fixture table. The mounting block and the contact end block are precision machined, whereas other components are purchased from vendors.

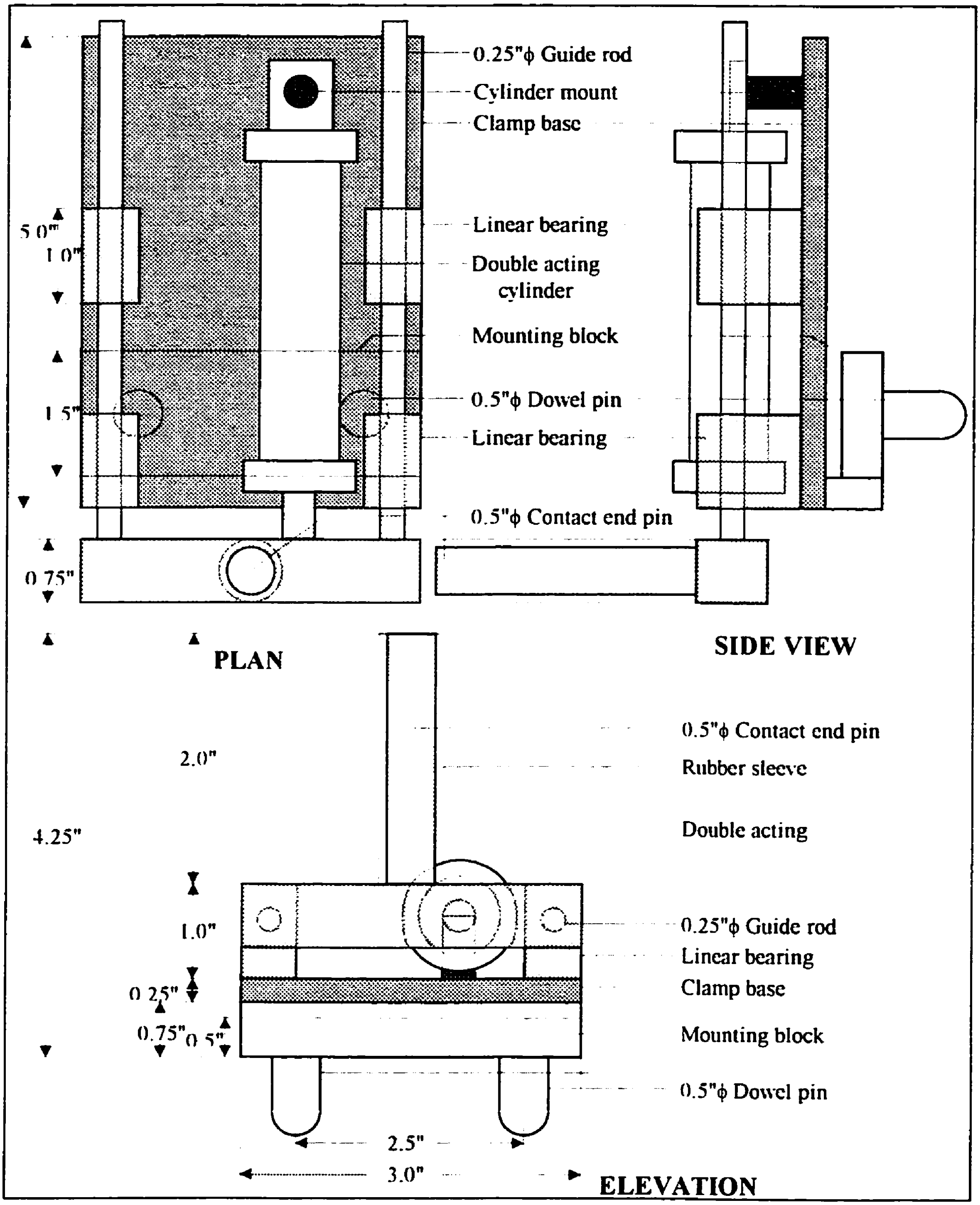


Figure 4.5: Horizontal clamp

4.3 Fixture stability

The deburring tool exerts a force on the workpiece during its operation. Depending on the location being deburred, the workpiece will be subjected to a lifting moment about the X, Y and Z axes. The workpiece should be clamped adequately to overcome the lifting moments and maintain a stable position throughout the deburring operation. In practice, an operator would intuitively select as many clamping locations as possible in order to ensure the workpiece's stability. As an example, the operator may conservatively select four locations to clamp a workpiece, which otherwise could have been achieved with just three strategically selected locations. Clamping locations selected by experience and intuition would be located closer to the edges of a workpiece. The spacing between them is also likely to be large. The parts dealt with are delicate so that redundant clamps may distort the part. The operator can come up with a certain clamping configuration for a certain part and employ the same configuration for similar parts. The operator has to go through this intuitive selection process repeatedly, when clamping dissimilar parts.

Although intuitive clamping methods perform satisfactorily, the repeatability of the clamping configuration cannot be ensured for a given workpiece by the subsequent selection process. Also, this process is time consuming and demands the operator's skill and effort. The process may also result in employing redundant clamps to fixture the workpiece. These drawbacks can be eliminated by strategically selecting the clamping locations for a given workpiece, based on a theoretical analysis. It is also important to select as few clamping locations as possible in order to reduce the complexity of the fixture control strategies. An analysis to select the clamp locations is presented next.

4.3.1 Analysis for selecting clamping locations

A sample part is shown in Figure 4.6. This part is considered solely for the purpose of developing a clamping methodology. The X, Y and Z axes are assumed, for simplicity, to pass through the center of mass of the workpiece, as illustrated in Figure 4.6. The deburring tool is assumed to exert a force, **F**, at point A on the workpiece. The vertical component of the deburring force, $\mathbf{F_v}$, will produce moments, $\mathbf{M_x}$ and $\mathbf{M_y}$ about the X and Y axis, respectively. The horizontal component of the deburring force, $\mathbf{F_h}$, will produce a moment $\mathbf{M_z}$ about the Z axis. The moments about the X and Y axis can be expressed as:

$$\mathbf{M_x = F_v \; x \; L_x}, \tag{4.1}$$

$$\mathbf{M_y = F_v \; x \; L_y}. \tag{4.2}$$

Similarly

$$\mathbf{M_z = F_h \; x \; L_z}. \tag{4.3}$$

Here $\mathbf{L_x}$ and $\mathbf{L_y}$ are the moment arm of $\mathbf{F_v}$ about the X and Y axis, while $\mathbf{L_z}$ is the moment arm of $\mathbf{F_h}$ about the Z axis, as shown in Figure 4.6. These moment arms will vary as the tool moves along the part's edge. Suction clamps are employed to "balance" the moments and provide stability to the workpiece. As the vertical clamping force ($\mathbf{F_c}$) as well as the horizontal sliding resistance force ($\mathbf{F_s}$) provided by the suction clamp can be obtained from the literature of the suction cup's manufacturer, the minimum distance required to locate the suction clamp from each axis can be determined from the following equations:

$$\mathbf{D_x = M_x \, / \, F_c}, \tag{4.4}$$

$$\mathbf{D_y = M_y \, / \, F_c}, \tag{4.5}$$

and

$$\mathbf{D_z = M_z \, / \, F_s}. \tag{4.6}$$

The suction clamps located at the above distances will provide equal but opposite moments to the deburring force's moments. As the vertical clamping force (F_c) and the horizontal sliding resistance force (F_s) provided by the suction clamp depend on the vacuum supply, variations in the vacuum level will affect the workpiece's stability. The balancing moment provided by a suction clamp about an axis increases with its distance from the axis. Balancing moments greater than the deburring force's moments can be achieved by locating the suction clamps at distances greater than the computed distances. Therefore, improved workpiece stability can be achieved by increasing the clamping distances to the maximum allowable limit. Also, the deburring force is assumed to act on a farthest point in the workpiece from each axis, to simulate a worst case scenario, in the force analysis.

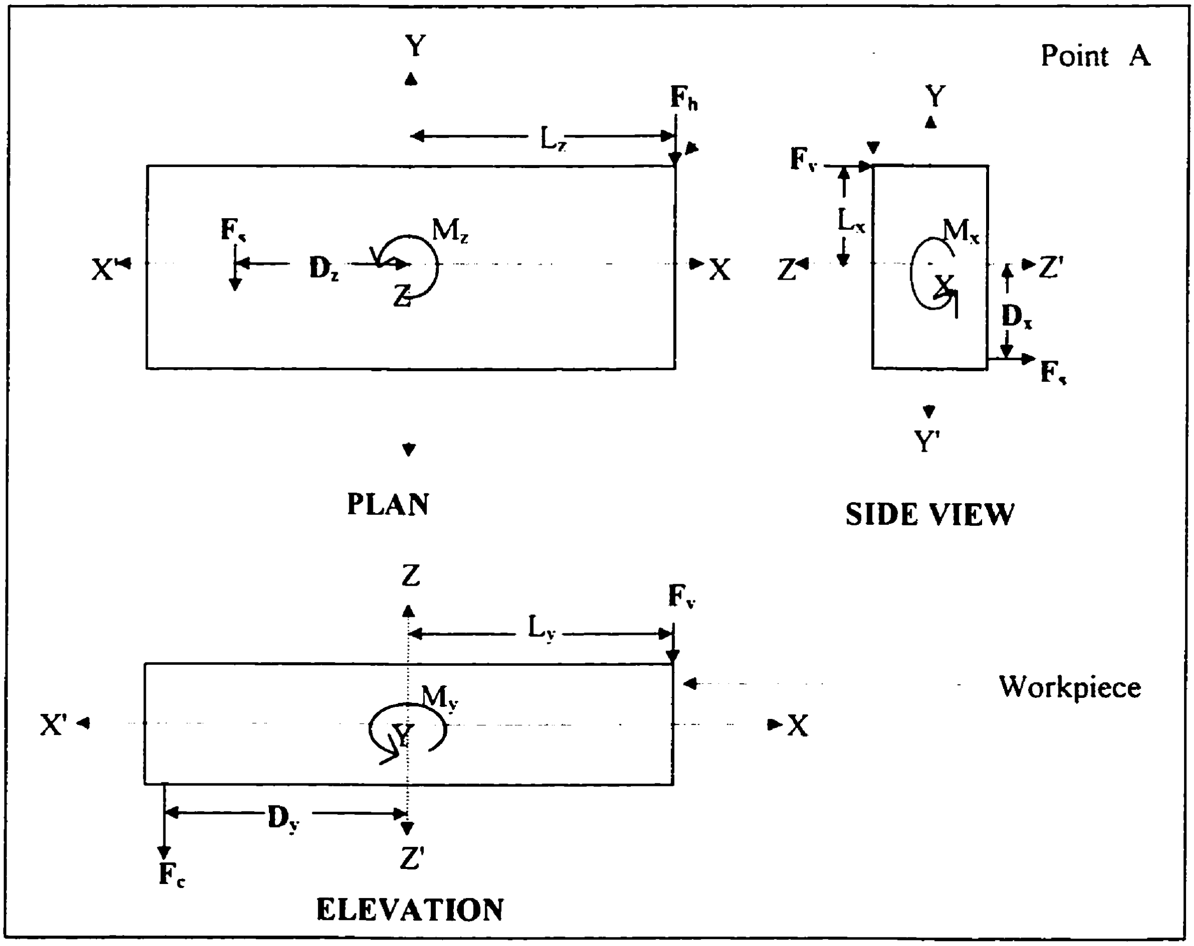


Figure 4.6: Analysis of workpiece forces

The following additional constraints have to be considered to determine a clamping location:

1) the presence of part features such as holes, flanges and cross ribs;

2) the suction cup's diameter;

3) the alignment of the dowel holes with the selected clamp locations; and

4) the minimum number of total clamping locations for the family of parts.

A stability analysis was performed for the representative part shown in Figure 4.7. The vertical clamping force provided by the suction cup is 16.4 lbf and the horizontal sliding resistance of the suction cup is 8.8 lbf. These values are determined from the vacuum generated by the pump, area of the suction cup as well as surface quality (e.g., how smooth). The deburring force generated by a cylindrical disc on a part's edge will range from 0.5 lbf to 1.0 lbf. This force depends on the value selected in the compliance device during the robot programming. The deburring force generated by a string brush on the part's edge will range from 1.0 lbf to 3.0 lbf. This force depends on the interference between the string and a part's edge. As the string brush generates a force upto 3.0 lbf, this largest value was considered for the stability analysis to simulate a worst case scenario.

The representative part shown in Figure 4.7 is 30" long with a maximum width of 12". The lug attached to the wider side of the part is 15" wide. The axes X-X' and Y-Y' shown in Figure 4.7 are assumed to pass through the part's center of mass. The force generated on an edge, farthest to an axis, produces the largest moment about that axis. Therefore, as a worst case scenario, the farthest edge to each axis is considered in this analysis. The vertical component of the deburring force at points **A** and **A'** will produce the maximum moments about the X-X' axis. On the other hand, the vertical component of the deburring force at points **B** and **B'** will produce the maximum moments about the Y-

Y' axis. The horizontal component of the deburring force at points **A** and **A'** will produce the maximum moments about the Z axis. The clamp locations can be determined by using equations **(4.1)** through **(4.6)**. A sample computation is illustrated in Appendix C.

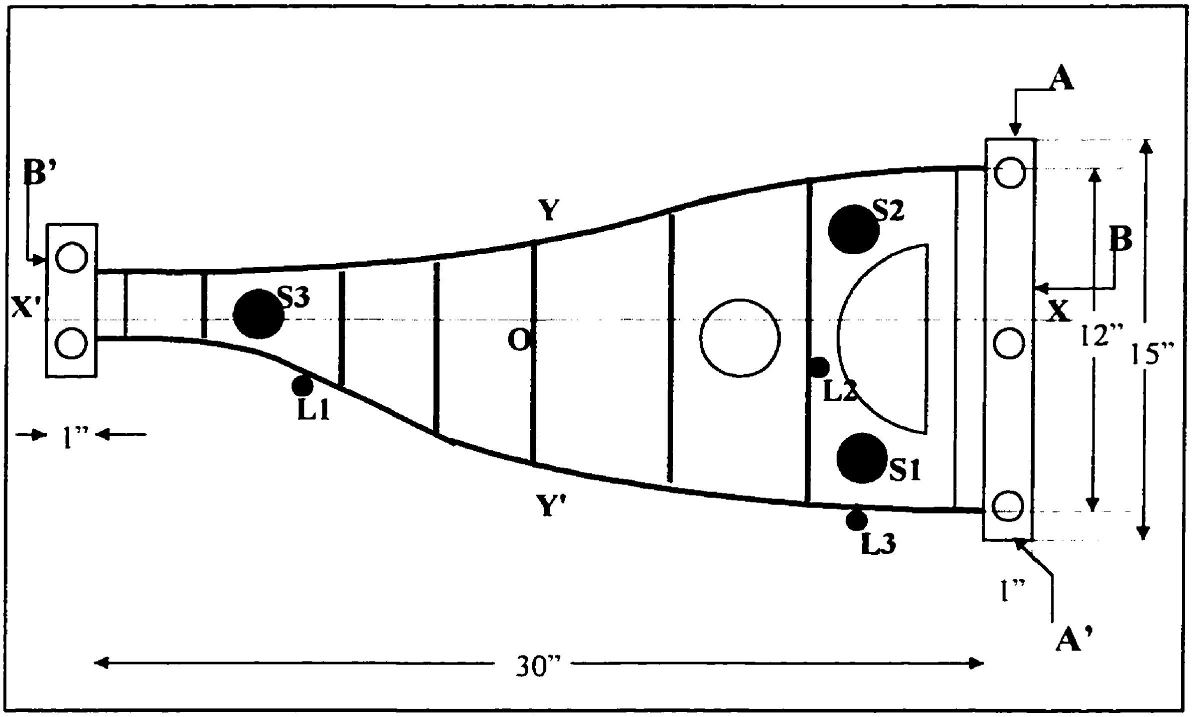


Figure 4.7: Representative part for force analysis

For the part considered, the suction clamps should be located at **1.46"** and **1.28"** along the positive and negative directions from the **X-X'** axis to balance the moment generated by the deburring force at points **A** and **A'**, respectively. Also, the suction clamps should be located **2.74"** along the positive and negative directions from the **Y-Y'** axis to balance the moment generated by the deburring force at points **B** and **B'**. Each suction clamp should be located at least **1.74"** from the Z axis to balance the moment generated by the deburring force at point **A or A'**. A similar analysis can be applied to the other parts and the clamping locations can be determined for each part. It should be noted that this analysis does not take into account other constraints such as the presence of holes or cross ribs that may be present on the part at the computed locations. These constraints are discussed next.

4.4 Location selection of fixture component

The most critical part of the fixture system is the location selection of the fixture components for a given part. Several constraints have to be satisfied during the selection process. The first constraint is the presence of alternative dowel and tapped holes in the base plate. The fixture components must align precisely with the dowel holes but still contact a point on a part profile's non-restricted region. The second constraint is the diameter of the vacuum suction cup. The suction cup must rest against a flat machined surface for efficient clamping. The complex features in a part (such as large holes, raised surfaces and rivet holes) reduce the area of the flat surfaces. The available clamping surfaces should allow the supporters to align precisely with the dowel holes. The third constraint is positioning the locators. When a part is in contact with all three locators, the supporters should be well within the clamping surface. The blocks of the base plate connector pose a major constraint in locating the supporter and locator pins. Each of the four blocks used to connect the three base plates occupies eight holes in the base plate. Also, the connector block interferes with the supporter clamping unit when an adjacent dowel hole is selected to mount a supporter module.

The above constraints were satisfied by using a manual iterative process. For a given part, the clamp locations were computed by using equations (4.1) through (4.6). The desired position and orientation of the part was determined and the part's X and Y axes were marked on the fixture table. Then the dowel holes that were present between the computed distances and the corresponding part's edges were listed. The dowel holes that interfered with the part's features, such as holes and cross ribs, were eliminated. A final set containing the possible clamping locations was obtained by further eliminating the holes that were within 0.5" of the part's edges. The supporter pin locations were selected from this final set such that, their locations were separated as far as possible to achieve the maximum stability. The dowel holes that were within 0.5" outside the part's edges were listed. Locator pin locations were selected from this list such that the locations were separated as far as possible yet they permitted contact with the part. The connector blocks can be removed once the base plates were attached firmly to the steel frame.

Operations performed on the Boeing-777 parts should also be considered while selecting the pin locations. The Boeing-777 components were processed in two stages, namely, the preliminary and final stages. In the preliminary stage, the sharp edges were chamfered to approximately 0.03" in order to expedite edge rounding during the final stage. Also, lugs and tabs were deburred to allow safe handling of the parts during (i) manual drilling of holes, (ii) dimensional inspection on a coordinate measuring machine, (iii) removal of lugs and tabs by manual routing and (iv) surface inspection using a liquid penetration inspection. Surface blending and edge rounding were performed in the final stage. Fixture components should not interfere with the tools that perform these last operations.

Fifty Boeing-777 parts were classified into four major groups based on a part's shape and complexity. Each group comprised geometrically similar parts as well as their mirror counterparts. A candidate part in each group was considered in order to determine the locations of the fixture component for the corresponding group. It was assumed initially (and verified later) that, if a candidate part could be fixtured with a particular configuration, all other parts in that group could also be fixtured with the same configuration. This procedure also applied to side-A of a part as well as side-B of its mirror counterpart. The representative parts and their pin locations are presented in the following sub sections.

4.4.1 Fixture component location for representative group-1 part

Group-1 parts have the most complex features. These parts are triangular in shape with a dimension of 2.5' x 1.25'. They have side flanges, cross ribs, inner web and lugs, as shown in Figure 4.6(a). Lugs are part of the stock that is used to clamp a part during manufacturing. Flanges have a maximum thickness of 0.2". Cross ribs and the web, on the other hand, have a maximum thickness of 0.1". These features are shown as thick lines in the schematic diagram. Both, the part profile and flange profile are constructed of cubic curves, as shown in Figure 4.6(a). Hence, the flanges are not perpendicular to the horizontal and vertical planes. The web is the only component whose surface is parallel to the horizontal plane. As this part is non-prismatic, point contacts are used to locate and constrain the part. The web surface is utilized to clamp the part on the base plate by using three vacuum suction clamps. Horizontal clamps can be located in several locations providing the clamping points are within the locator span. The supporter and locator pin locations are selected by using the selection method mentioned earlier for both sides of the part. Both the computed and the selected pin locations are presented in Table 4.1. The selected pin locations for both sides A and B are shown in Figures 4.8(a) and 4.8(b), respectively.

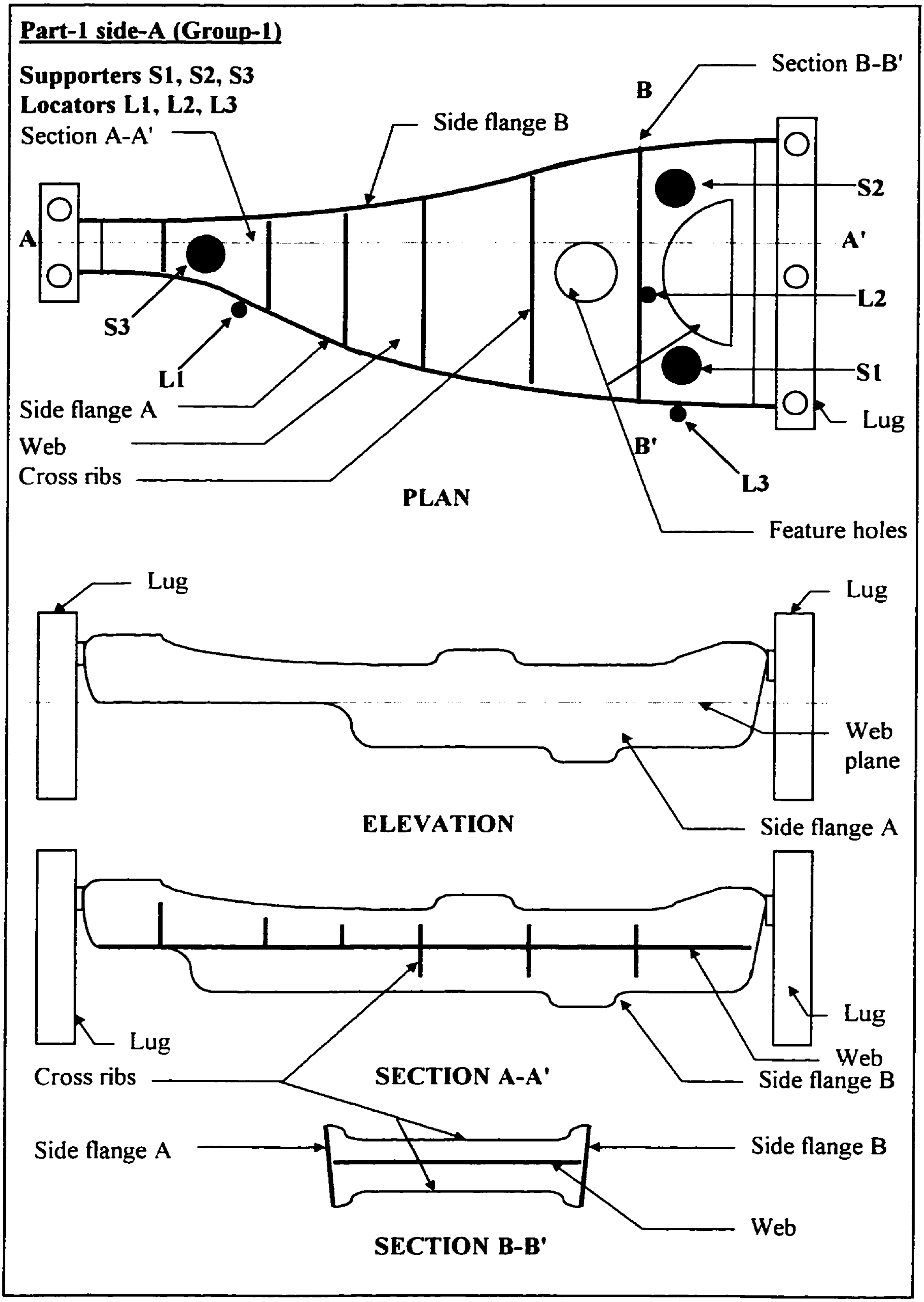


Figure 4.8(a): Pin locations for part representative of Group-1

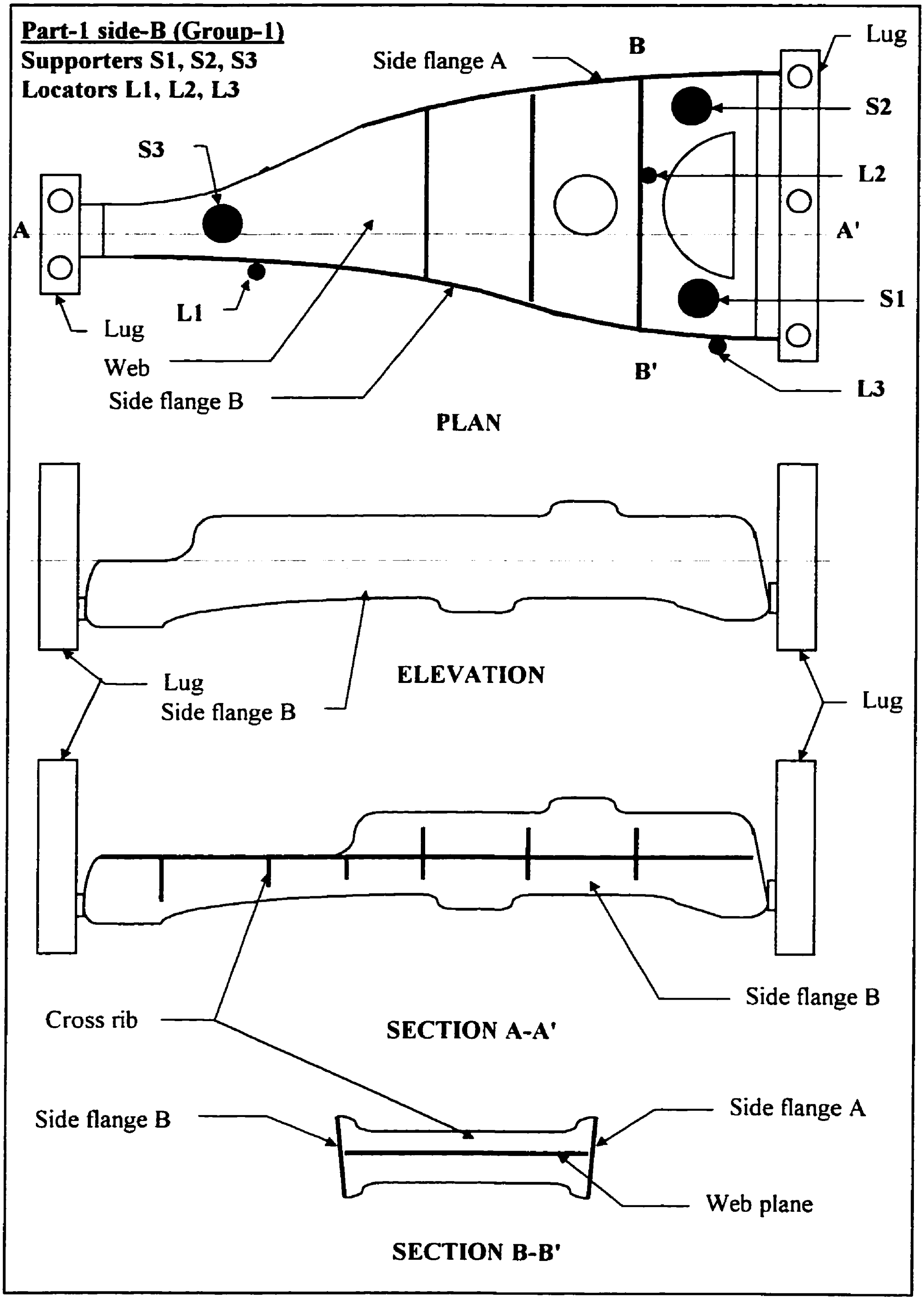


Figure 4.8(b): Pin locations for part representative of Group-1

4.4.2 Fixture component location for representative group-2 part

Group-2 parts are almost rectangular in shape with dimensions of approximately 1.5' x 1', as shown in Figure 4.8(c). The side flanges, cross ribs and web have a maximum thickness of 0.1". Hence, these parts are more flexible in comparison to group-1 parts. As the group-2 parts are thin and flexible, four supporters are used to clamp the part as shown in Figure 4.8(c). As mentioned earlier, horizontal clamps can be located in several locations as long as the clamping points are within the locator span. The supporter and locator pin locations are selected by using the selection method mentioned earlier for both sides A and B of the part. Both the computed and selected pin locations are presented in Table 4.1. The supporter and locator pin locations are shown in Figure 4.8(c) for both sides A and B.

4.4.3 Fixture component location for typical group-3 part

Group-3 parts resemble a narrow channel with dimensions of 2.5' x 0.25', as shown in Figures 4.8(d) and 4.8(e). The flanges and web have a maximum thickness of 0.2" and the cross ribs are 0.1" thick. Hence, these features are shown as thick lines in the diagram. The shape variation for the group-3 parts is shown in Figure 4.8(f). The part shown in Figure 4.8(f) resembles a L-shaped channel and it is 3' long. The web surface of a group-3 part is 3" wide and this width is sufficient to locate the vacuum suction cups to clamp a part on the base plate. The narrow shape of these parts poses a major constraint in selecting appropriate supporter and locator pin locations. The horizontal clamps can be located in several locations if the clamping points are again within the locator span. The supporter and locator pin locations are selected, as before, for sides A and B. Both the computed and selected pin locations are presented in Table 4.1. The supporter and the locator pin locations are shown in Figures 4.6(d), 4.8(e) and 4.8(f), respectively, for both sides A and B of three group-3 parts.

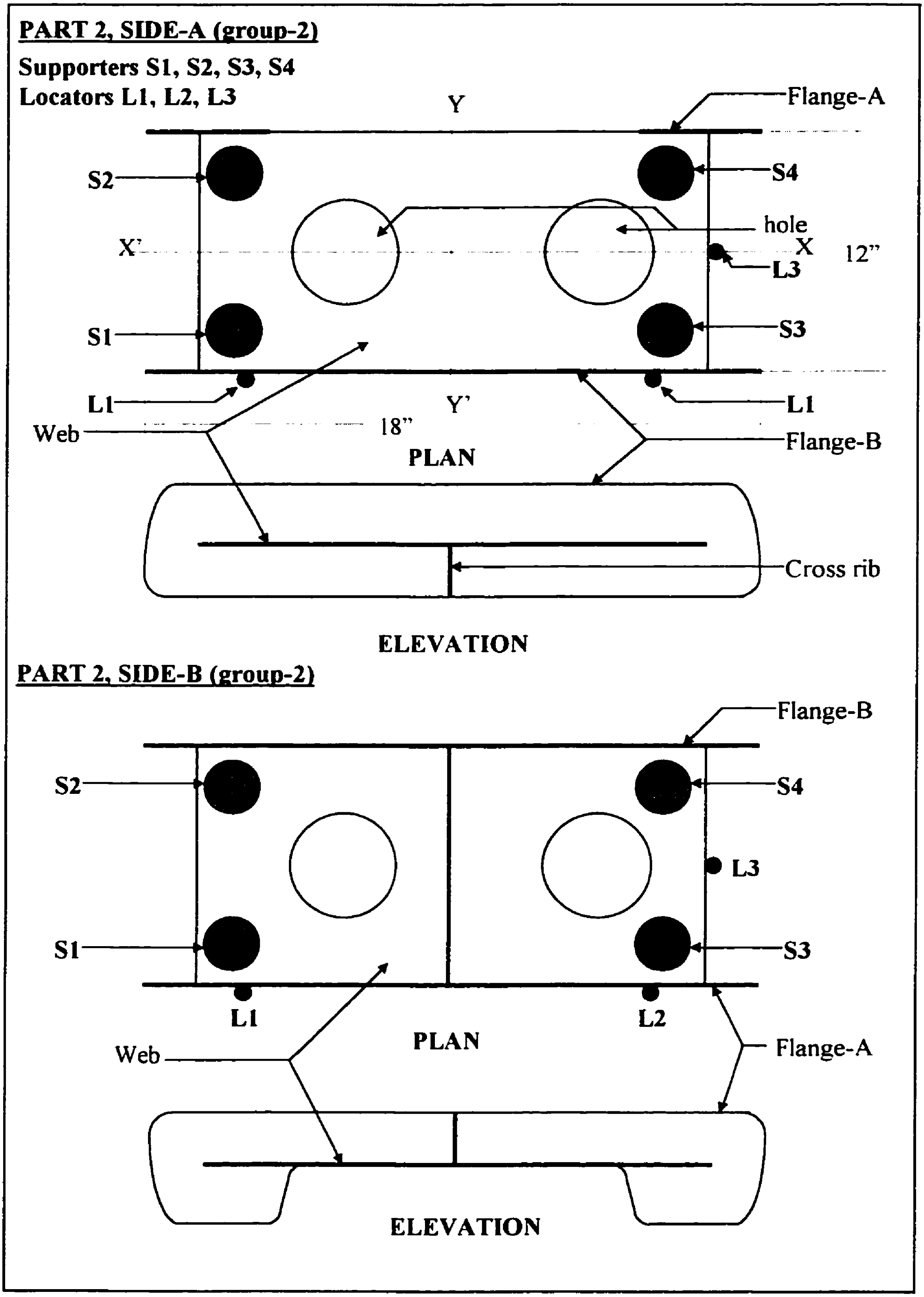


Figure 4.8(c): Pin locations for part representative of Group-2

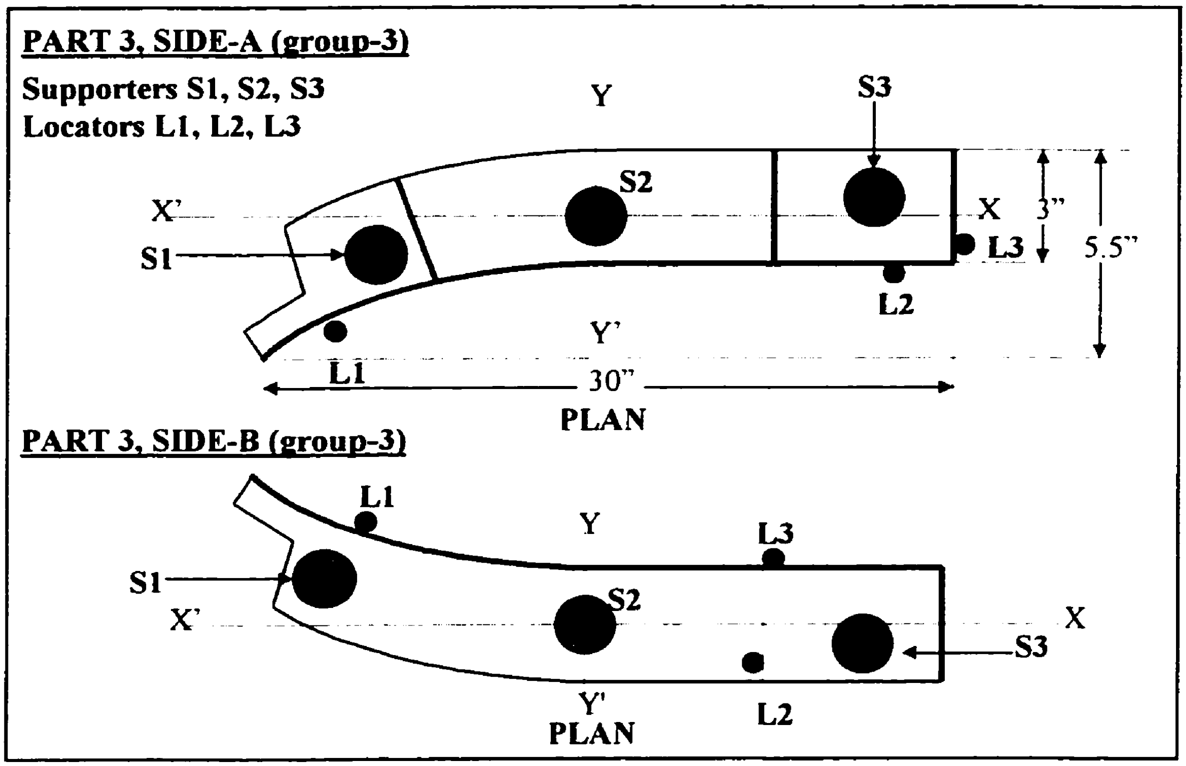


Figure 4.8(d): Pin locations for part representative of Group-3

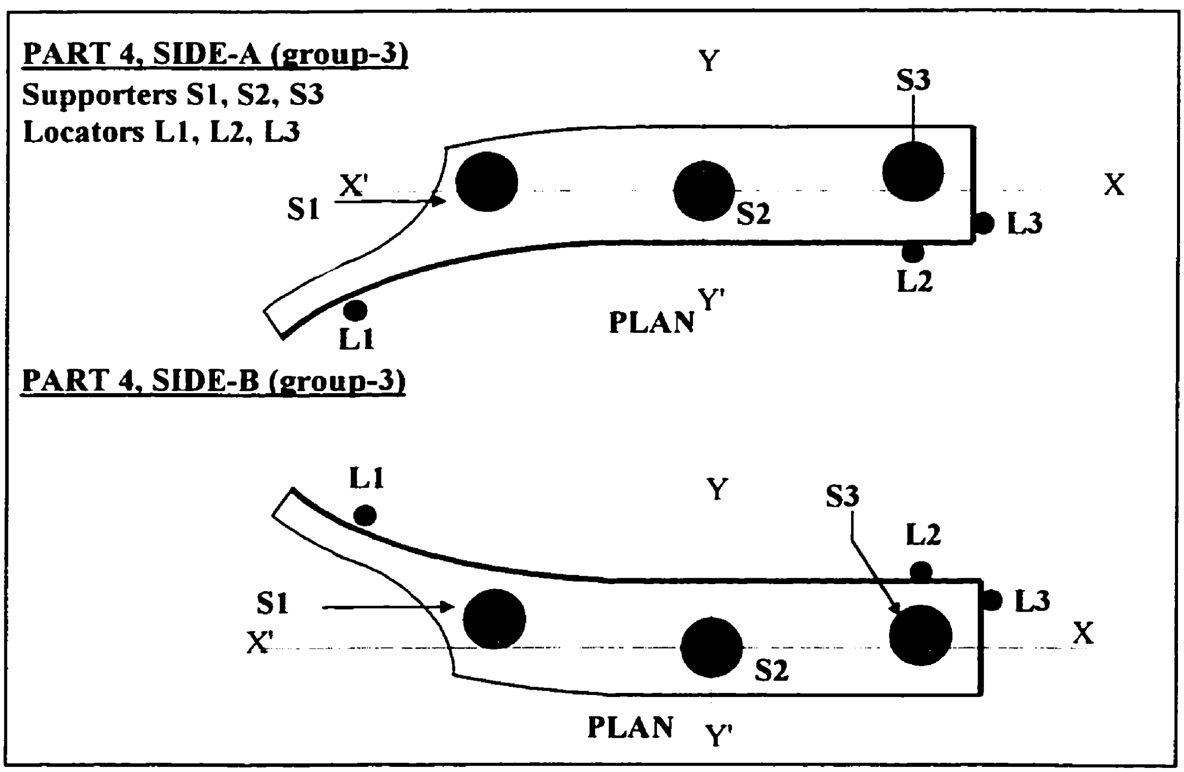


Figure 4.8(e): Pin locations for part representative of Group-3

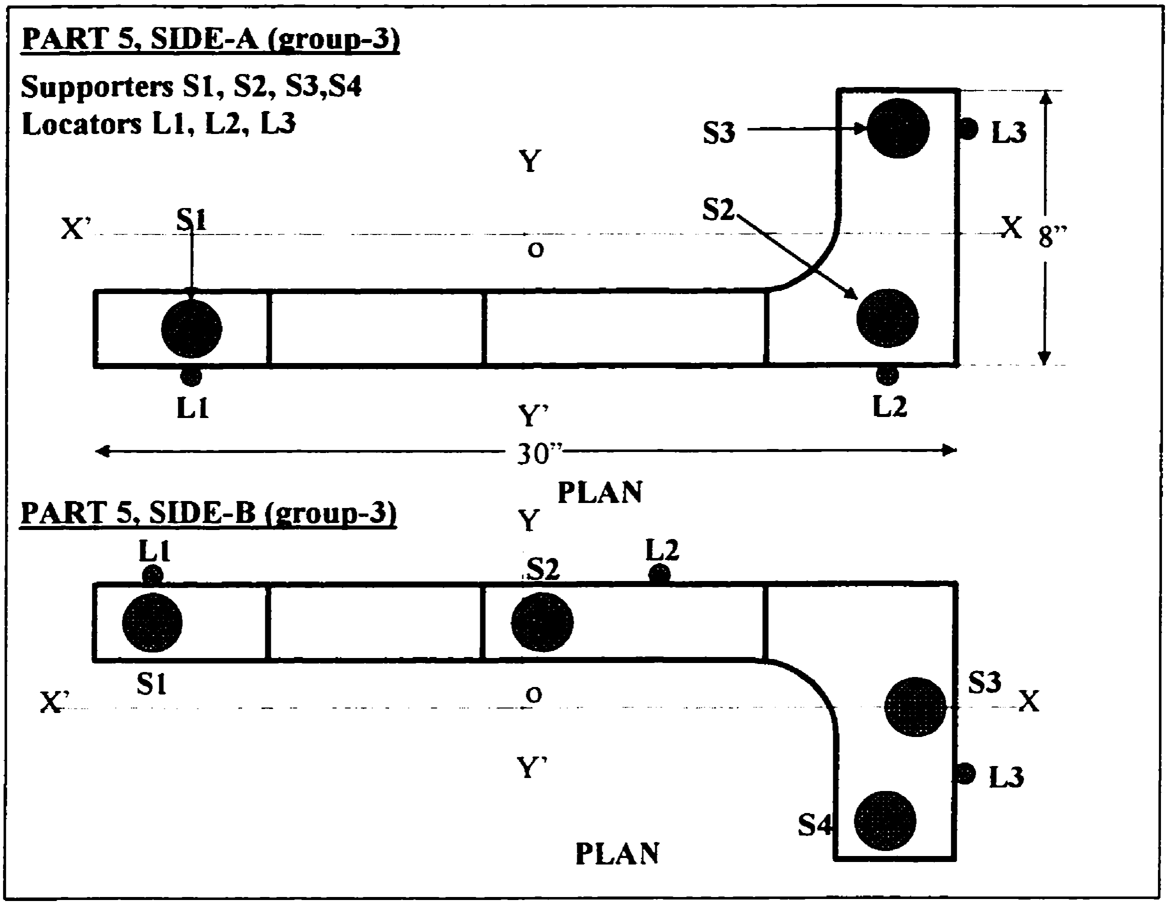


Figure 4.8(f): Pin locations for part representative of Group-3

4.4.4 Fixture component location for typical group-4 part

The group-4 parts have the shape of a trapezoidal frame with overall dimensions of approximately 1.5' x 1', as shown in Figure 4.8(g). The side flanges, cross ribs and the web have a maximum thickness of 0.2". These parts are essentially rigid due to their frame-like structure. The web surface of the group-4 parts are 2.5" wide and there is minimal space to locate the vacuum suction cups in order to clamp the part on the base plate. The narrow frames of these parts pose a major constraint in selecting the supporter and locator pin locations. As before, the horizontal clamps can be located in several locations if the clamping points are within the locator span. The supporter and locator pin locations were selected by using the selection method described in section 4.3. Both the computed and selected pin locations are presented in Table 4.1. The supporter and locator pin locations for both sides A and B of this part are shown in Figure 4.8(g).

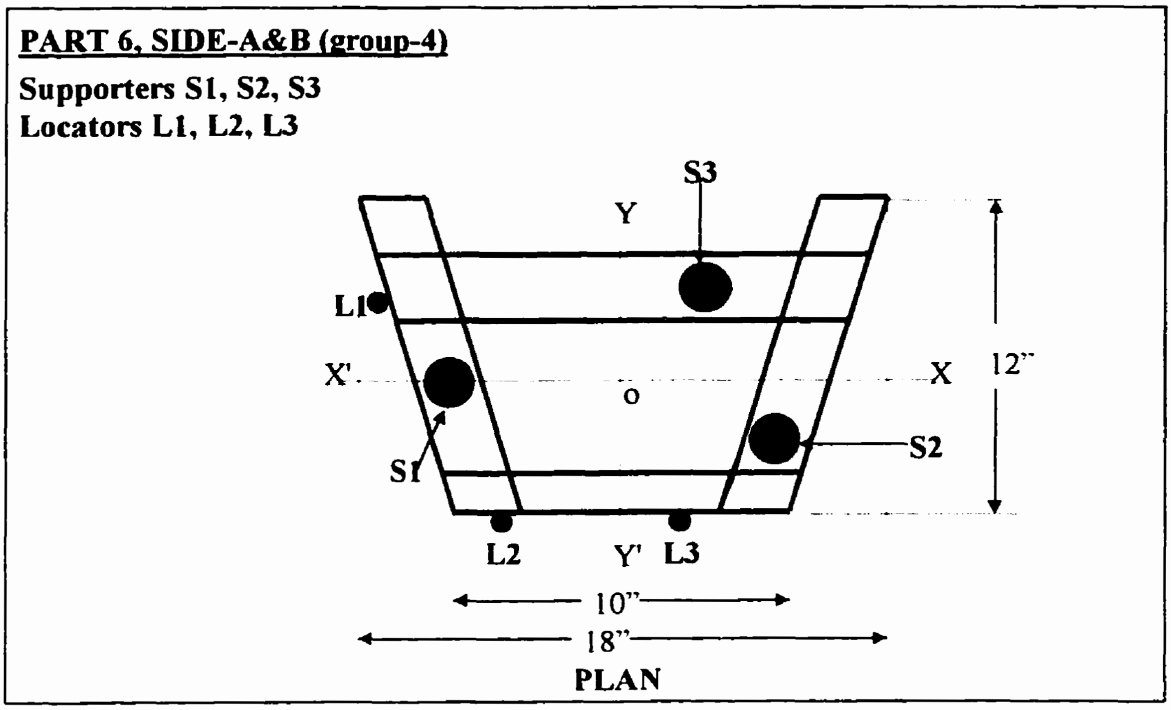


Figure 4.8(g): Pin locations for part representative of Group-4

The aluminum aircraft parts considered in this study weigh between 3 to 5 lb. Also, these parts experience a low cutting force that ranges from 0.5 to 3 lbf. The fixture system employs at least three vacuum suction cups to clamp a part. As each suction cup can produce a clamping force of 16.4 lbf, the part is held on the fixture table with a total vertical clamping force of approximately 49.2 lbf. Also, because each suction cup can provide a sliding resistance of 8.8 lbf, the part is prevented from rotating and sliding with a total resistance of approximately 26.4 lbf. The horizontal clamps are employed mainly to locate the part against the locator pins because the main clamping of the part is achieved by employing the vacuum suction cups. The computed and selected clamping distances for all the representative parts are presented in Table 4.1.

Part ID	Computed clamping distance from axis on X-Y plane (inch)			Supporter Pin	Selected clamping distance from axis on X-Y plane (inch)		
	X axis	Y axis	Z axis		X axis	Y axis	Z axis
Part1 A	1.46	2.74	1.74	S1	-3.0	12	12.34
	-1.28	-2.74		S2	2.0	12	12.17
				S3	0.25	-11.75	11.75
Part1 B	1.28	2.74	1.74	S1	-2.0	12	12.17
	-1.46	-2.74		S2	3.0	12	12.34
				S3	-0.25	-11.75	11.75
Part2 A/B	1.1	1.65	0.77	S1	-2.5	-7.5	7.9
	-1.1	-1.65		S2	2.5	-7.5	7.9
				S3	-2.5	7.5	7.9
				S4	2.5	7.5	7.9
Part3 A	0.73	2.74	1.71	S1	-1.25	-8.75	8.75
	-.36	-2.74		S2	0	0	0
				S3	1.25	11.25	11.25
Part3 B	0.36	2.74	1.71	S1	0	-12.5	-12.5
	-0.73	-2.74		S2	0	0	0
				S3	1.25	11.25	11.25
Part4 A	0.73	2.74	1.71	S1	-1.25	-8.75	8.75
	-.36	-2.74		S2	0	0	0
				S3	1.25	11.25	11.25
Part4 B	0.36	2.74	1.71	S1	1.25	-8.75	8.75
	-0.73	-2.74		S2	0	0	0
				S3	-1.25	11.25	11.25
Part5 A	0.73	2.74	1.71	S1	-2.5	-11.5	11.77
	-0.73	-2.74		S2	-2.5	13.12	13.36
				S3	4.79	13.5	15.01
Part5 B	0.73	2.74	1.28	S1	2.5	-11.32	11.59
	-0.73	-2.74		S2	2.5	0	2.5
				S3	0	12.5	12.5
				S4	-4.79	9.6	10.73
Part6 A	1.1	1.65	1.02	S1	0	-5.0	5.0
	-1.1	-1.65		S2	-3.0	4.5	5.4
				S3	2.0	2.0	2.83
Part6 B	1.1	1.65	1.02	S1	0	-5.0	5.0
	-1.1	-1.65		S2	-3.0	4.5	5.4
				S3	2.0	2.0	2.83

Table 4.1: Computed and actual clamping distances

The selection of the pin locations reveals that a total of 9 supporter pin locations and 22 locator pin locations are sufficient to fixture most of the Boeing-777 parts considered. The identified pin locations on the fixture table are shown in Figure 4.8(h). The coordinates of the dowel holes on the fixture table, that correspond to the pins S1, S2, S3, S4, L1, L2 and L3 for all the previously mentioned parts, are presented in Table 4.2. The holes are labeled 1 through 48 along the fixture table's length and A through P along its width. Also, the horizontal clamps have a 3" travel along their length and, hence, their locations are not very critical. The horizontal clamps can be located in several locations providing the clamping point is within the locator span. These clamps can also be mounted underneath the part to obtain a point contact with the cross rib. The pin location information presented in Table 4.2 is stored in the fixture's controller and the appropriate fixture components are activated to fixture a given part. If a programmable logic controller is made available, this information could be programmed conveniently into the ladder logic sequence. Then, whenever a given part is identified, information about the appropriate fixture configuration could be retrieved and the corresponding pins could be activated automatically.

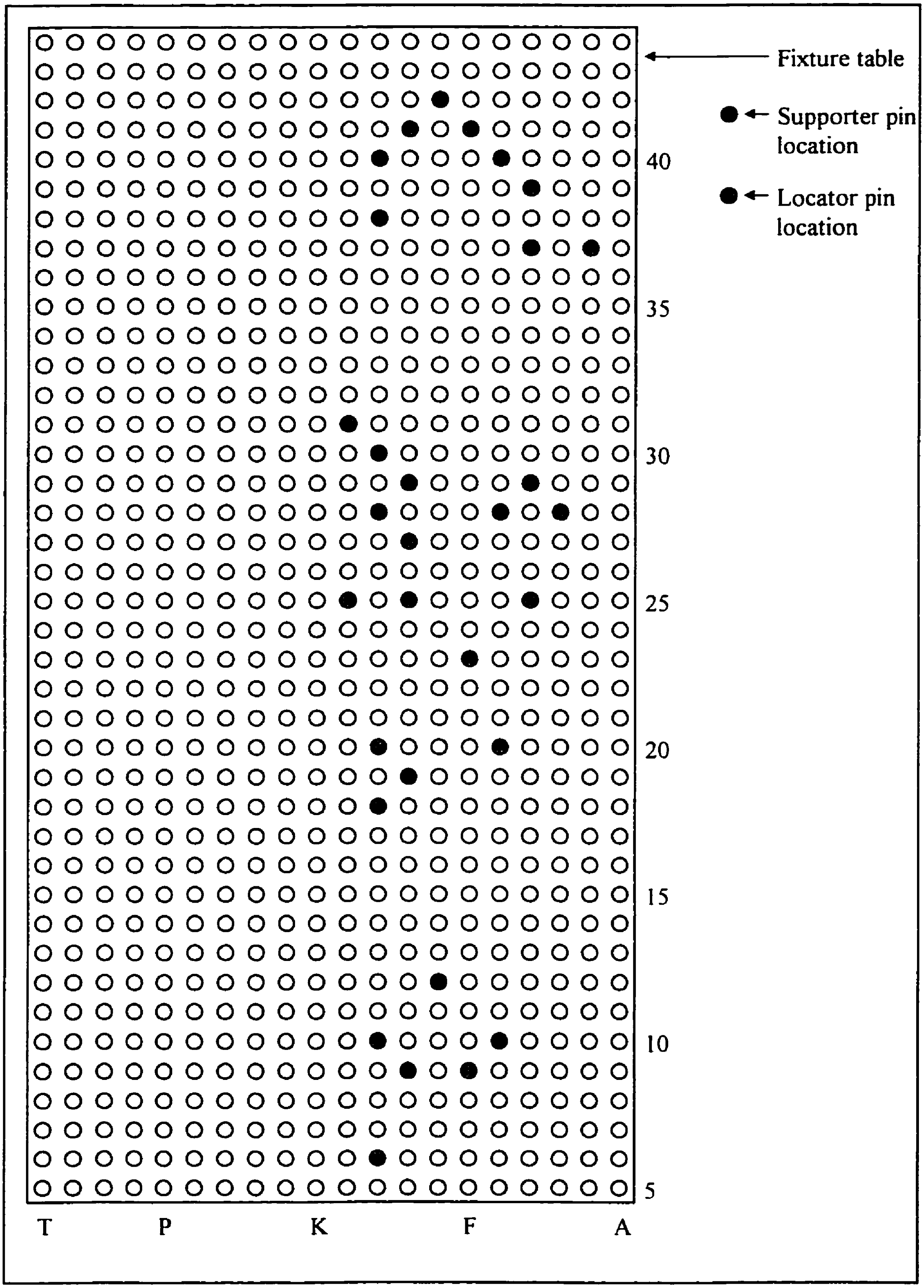


Figure 4.8(h): Supporter and locator pin locations on the fixture table

Part ID	Supporter pin locations				Locator pin locations		
	S-1	**S-2**	**S-3**	**S-4**	**L-1**	**L-2**	**L-3**
Part1-A	E-28	I-28	H-9		F-9	H-27	C-28
Part1-B	E-28	I-28	H-9		F-9	H-27	C-28
Part2-A	E-28	I-28	E-40	I-40	D-29	D-39	G-42
Part2-B	E-28	I-28	E-40	I-40	D-29	D-39	G-42
Part3-A	G-12	H-19	I-28		E-10	H-29	I-30
Part3-B	H-9	H-19	I-28		I-10	H-25	J-25
Part4-A	G-12	H-19	I-28		E-10	H-29	I-30
Part4-B	G-12	H-19	I-28		I-6	J-25	I-30
Part5-A	H-19	D-37	I-40		F-23	B-37	H-41
Part5-B	H-19	I-28	I-38	E-40	I-20	J-31	F-41
Part6-A	H-19	E-28	I-28		I-18	E-20	D-25
Part6-B	H-19	E-28	I-28		I-18	E-20	D-25

Table 4.2: Supporter and locator pin coordinates on the fixture table

4.5 Fixture control

The fixture system can be assembled and operated either manually or automatically. However, manual methods are not desirable because of the labor cost. Therefore, the objective is to minimize manual interference as much as possible. One possibility would be to automatically control the fixture assembly and operations. Fixture automation includes the control of the fixture's operation as well as the continuous monitoring and signaling of the status of the fixturing and deburring. This was achieved by employing a controller with the necessary interface modules and control logic.

The interface module comprises the power supply blocks, isolator relays, solenoid valves and pneumatic air supply. This module remains the same, irrespective of the type of device selected to control the fixture system. Hence, the selection criteria are based on the cost of the device, its capability, programmability and reliability, and the cost of acquiring or developing the control software. The concept of modularity is also considered when planning the automation strategies and selecting the appropriate control devices. The employed modularity enables the use of two or more fixture systems in the same cell, subject to the space availability in the robot's work envelope as well as the accessibility of the robot. Therefore, the fixture control can be classified into two systems, namely the control of the fixture's operation and the overall control of the cell. These two systems communicate with the robot's controller to efficiently perform the robotic fixture assembly and deburring operations. The two systems are presented next.

4.5.1 Operation of fixture control

The fixture operation begins with the identification of the part to be deburred. Each part has to be fixtured on both sides to allow the complete deburring operation to occur in two steps. The fixture controller is designed to identify each side of the part as an artificially separate part in order to simplify the control tasks. Once the "part" is identified, the supporters and the locators are assembled on the base plate at the appropriate locations. This operation is performed manually presently. However, it can be automated fully by employing the robot to place all the fixture components at the chosen locations. The supporters are locked in position and the part is placed on the fixture. Then the horizontal clamps are actuated. The orientation of the part is verified by checking the part's contact with the locator pins. The corresponding vacuum pumps are actuated after confirming the correct orientation of the part. The robot is signaled to perform the deburring. Once the deburring is completed, the horizontal clamps and vacuum pumps are deactivated. Then the operator is signaled to remove the part. The supporters are unlocked after the part is removed from the fixture. The fixture operation is complete only when the supporters and locators are removed from the base plate.

The fixture controller is required to perform various tasks which are based on the process conditions. Typically, these tasks are ON/OFF control to either activate or deactivate the process control elements. A programmable logic controller (PLC) is considered as an ideal candidate to be employed as the fixture controller because of its ability to efficiently perform logistic functions. A PLC utilizes digital inputs and it controls a process with digital outputs. Moreover, a PLC is a cyclic controller in that it scans through all the inputs, analyzes and outputs on a repetitive basis. The sequence for the PLC control is described below.

1) The robot / computer / operator signals the PLC to start the fixture cycle.
2) The PLC starts the fixture cycle and waits for the part ID.
3) The robot / computer / operator sends the part ID to the PLC.

4) The PLC recognizes the part ID and actuates (unlocks) the appropriate supporter clamps to allow the robot / operator to insert the supporter stems in the fixture location.
5) The PLC signals the robot / computer / operator that the fixture table is ready to be loaded, and also, to load the supporter and locator pins onto the table.
6) The robot / operator inserts the pins into the selected fixture locations and then signals the PLC that the pins are loaded.
7) The PLC actuates (locks) the appropriate supporter clamps.
8) The PLC signals the robot / operator to load the part onto the fixture.
9) The robot / operator loads the part onto the fixture and signals the PLC that the part is loaded.
10) The PLC actuates (extends) the horizontal clamps and checks the locator pin contacts.
11) If any of the contacts is not established, the PLC deactivates the clamps and signals the robot / operator to check the part's orientation.
12) If all contacts are established, the PLC actuates (turns ON) the vacuum pumps.
13) The PLC signals the robot controller that the part is fixtured and to start processing.
14) The robot processes the part and signals the PLC upon completion.
15) The PLC actuates (retracts) the horizontal clamps and then actuates (turns OFF) the vacuum pumps.
16) The PLC signals the robot / operator to remove the part from the fixture.
17) The robot / operator removes the part from the fixture and signals the PLC that the part is removed.
18) The PLC actuates (unlocks) the appropriate supporter clamps and signals the robot / operator to remove the pins.
19) The robot / operator removes the pins and signals the PLC that the pins are removed.
20) The PLC ends the fixture cycle and signals the robot / operator that the fixture cycle is complete.

The control logic program for the fixturing is developed for four sample parts. Deburring is performed on both sides of each part. The fixture table is assumed to be equipped with five supporter clamps that are tagged by the numbers 1 through 5. These clamps are located strategically underneath the base plate. The supporter requirement for each part is shown in Table 4.3. In this table, the term 'Part-1-A', for example, represents side A of part number 1. The information required to support all the parts is stored in the PLC logic program.

Part ID	Support-1	Support-2	Support-3	Support-4	Support-5
Part-1-A	Y	Y	Y		
Part-2-A		Y	Y		Y
Part-3-A	Y		Y		Y
Part-4-A	Y	Y			Y
Part-1-B	Y	Y	Y		
Part-2-B		Y	Y	Y	
Part-3-B	Y		Y	Y	
Part-4-B	Y	Y		Y	

Table 4.3: Supporter requirements for four sample parts

The employed programmable logic controller (OMRON: Sysmac C28K) is equipped with 14 input channels and 12 output channels. The capacity of the PLC is taken into account when developing the control logic program. The fixture system requires 19 input and 13 output channels. As the identification number of a part is provided to the PLC in binary format, at least 9 input channels are required in order to identify eighty parts. As the PLC has only 14 input channels, only 4 input channels (channels 1 through 4) are assigned for the part identification. Up to sixteen parts can be identified with this assignment. The PLC input assignment is shown in Table 4.4. As the PLC has only 12 output channels, the twelfth channel is assigned to both outputs 12 and 13. The PLC output assignment is shown in Table 4.5. The PLC control logic program for the fixturing system is presented in Figures 4.9(a) through 4.9(h).

Input #	Description	Input #	Description
1	Part number (Bit-0)	8	Start cycle. Signal from robot.
2	Part number (Bit-1)	9	Identify part. Signal from robot.
3	Part number (Bit-2)	10	Pins assembled. Signal from robot.
4	Part number (Bit-3)	11	Part loaded. Signal from robot.
5	Locator-1 contact	12	Process done. Signal from robot.
6	Locator-2 contact	13	Part unloaded. Signal from robot.
7	Locator-3 contact	14	Pins removed. Signal from robot.

Table 4.4: PLC input assignment

Output #	Description	Output #	Description
100	Supporter-1 latch UNLOCK	107	Vacuum pumps ON.
101	Supporter-2 latch UNLOCK	108	Insert Pins. Signal to robot.
102	Supporter-3 latch UNLOCK	109	Load part. Signal to robot.
103	Supporter-4 latch UNLOCK	110	Start processing. Signal to robot.
104	Supporter-5 latch UNLOCK	111	Unload part. Signal to robot.
105	Horizontal clamp-1 ON	111	Remove Pins. Signal to robot.
106	Horizontal clamp-2 ON		

Table 4.5: PLC output assignment

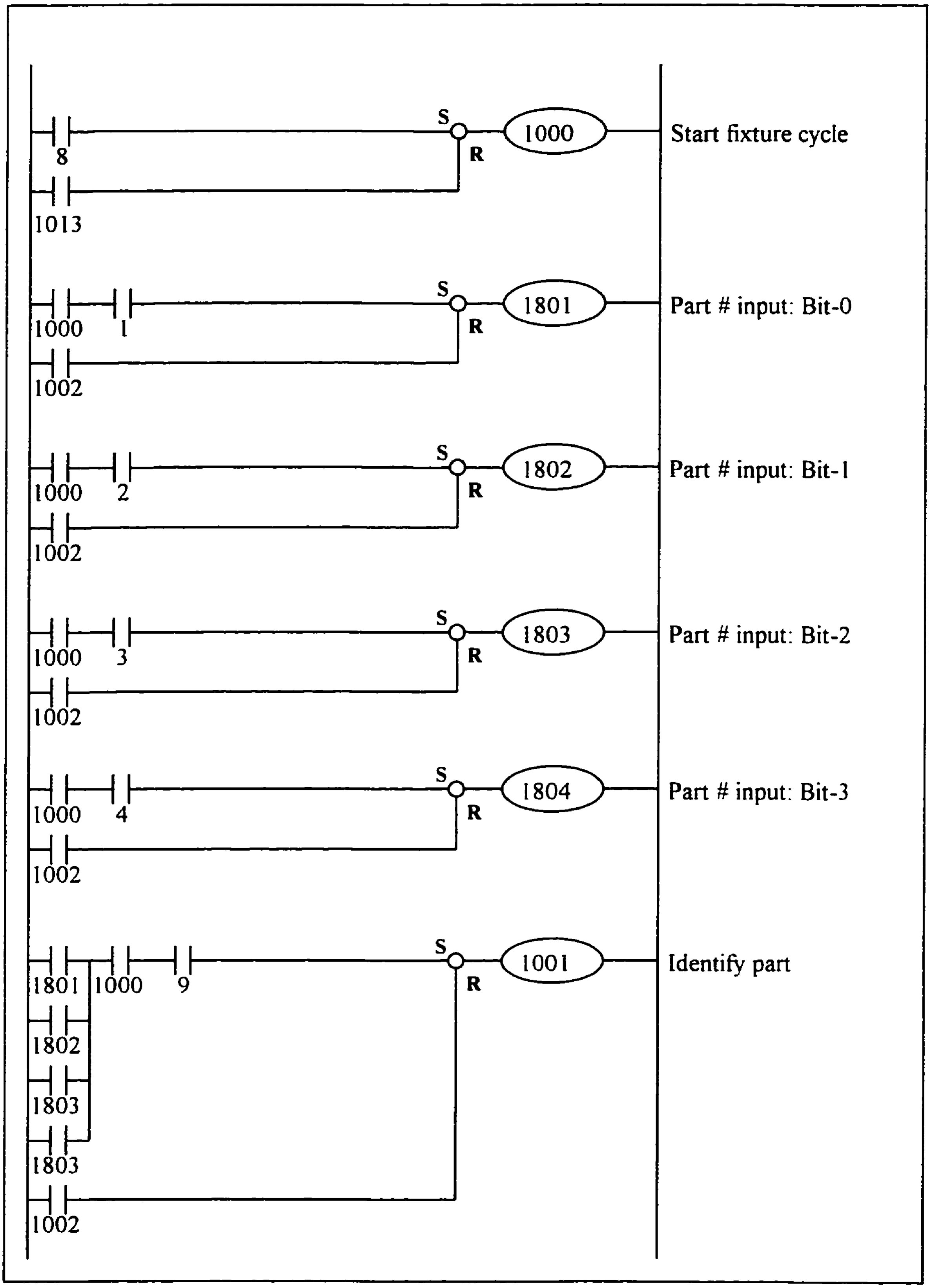


Figure 4.9(a): PLC logic to control the fixture

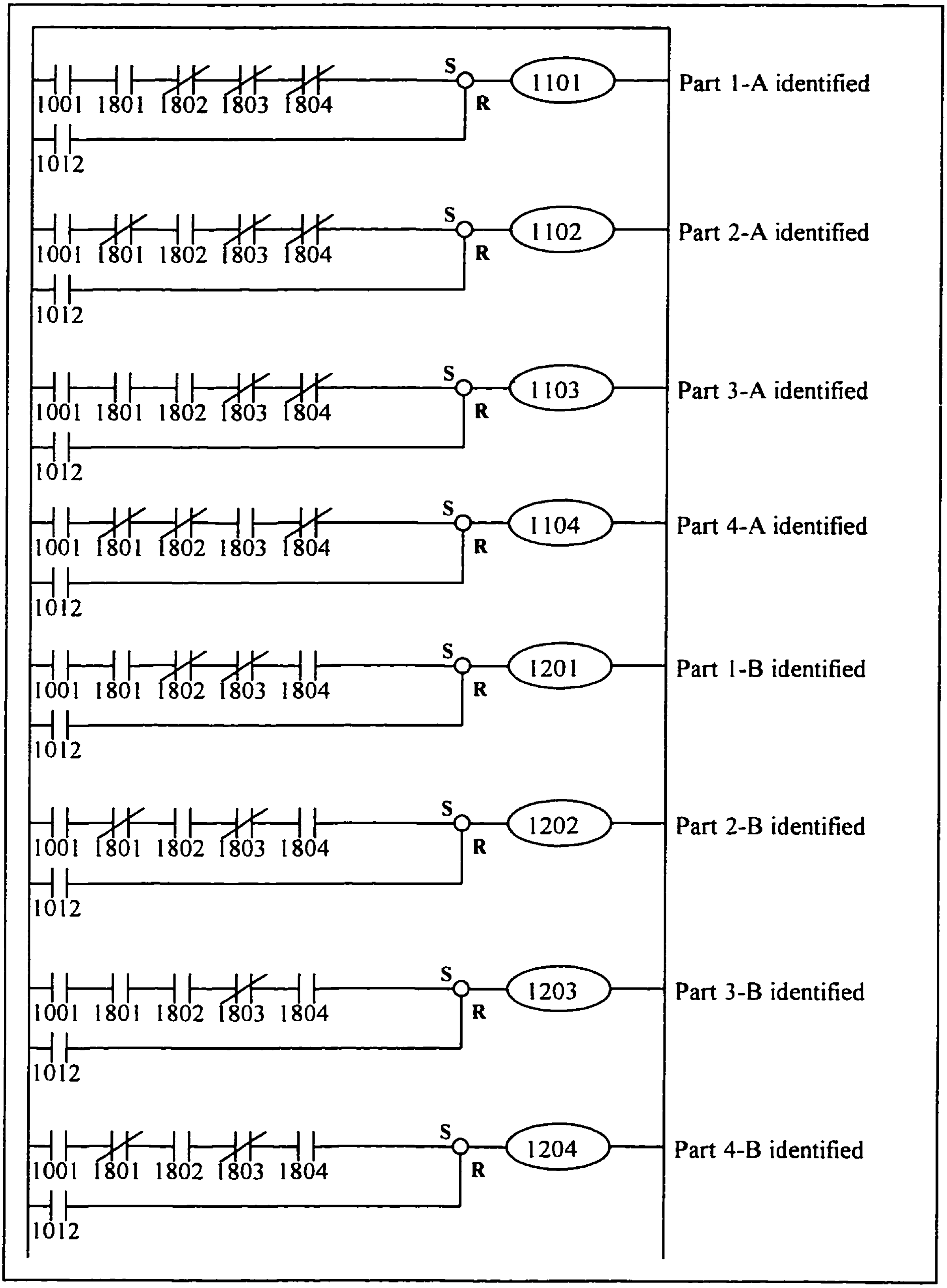


Figure 4.9(b): PLC logic to control the fixture

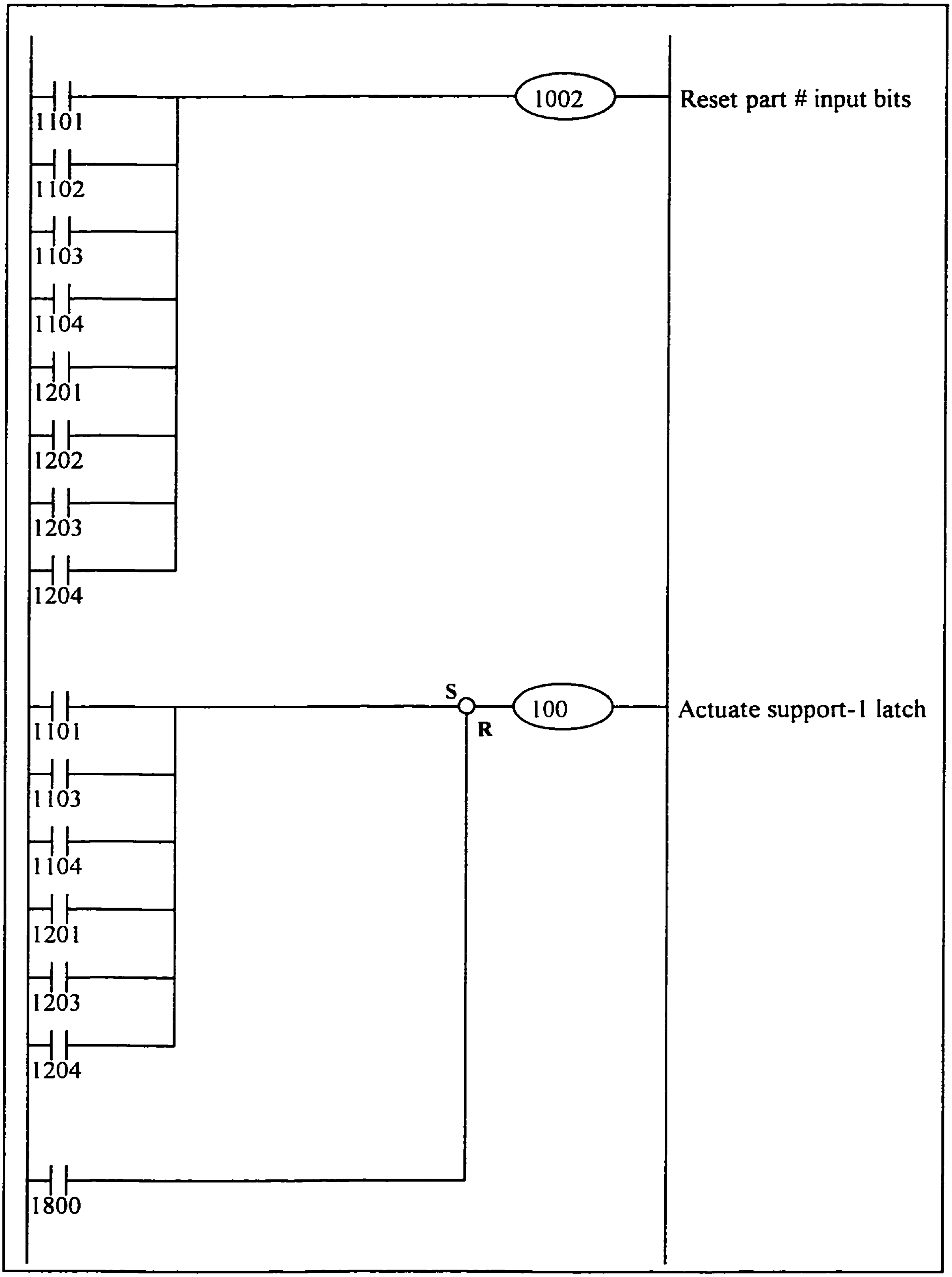


Figure 4.9(c): PLC logic to control the fixture

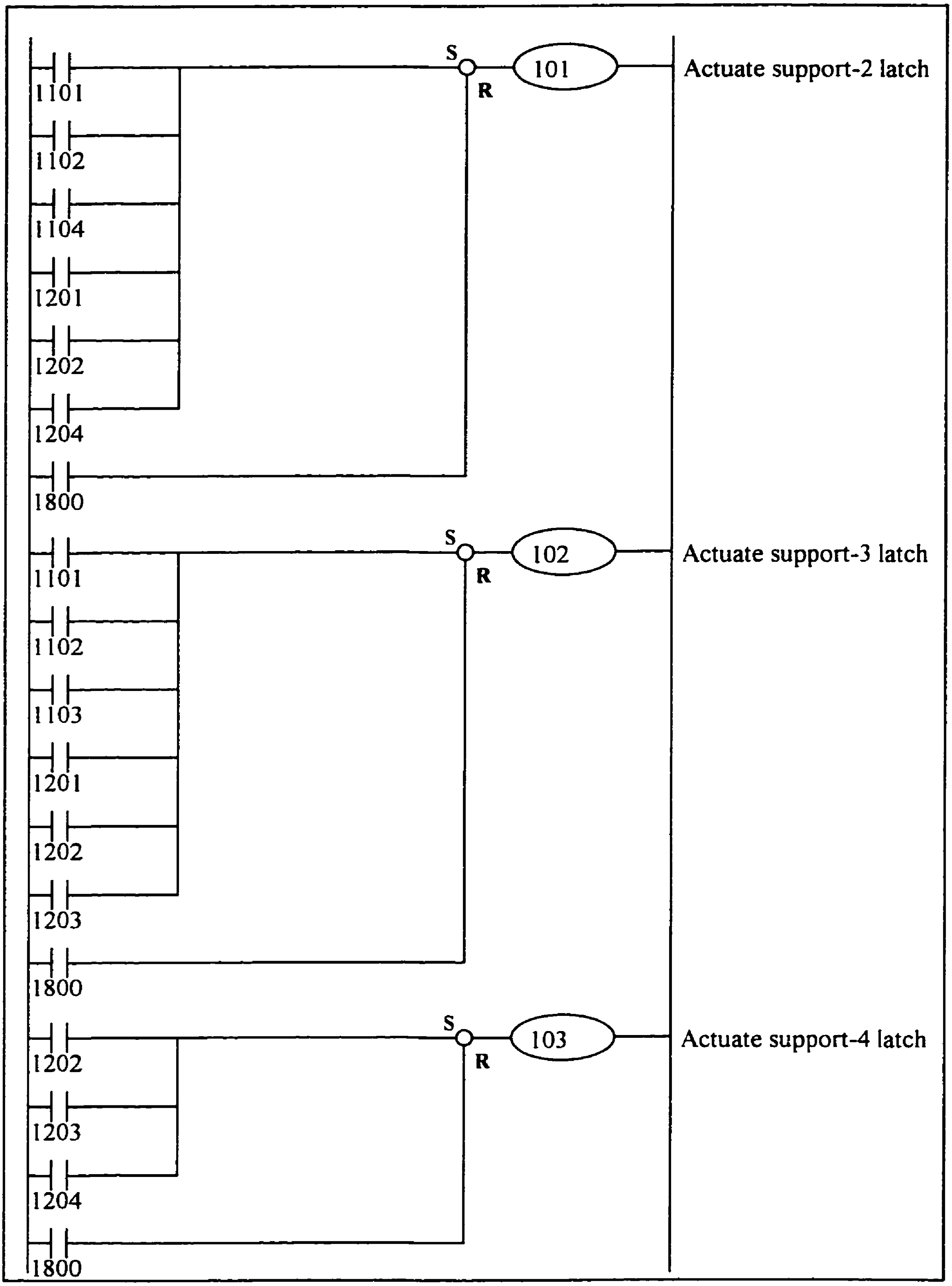


Figure 4.9(d): PLC logic to control the fixture

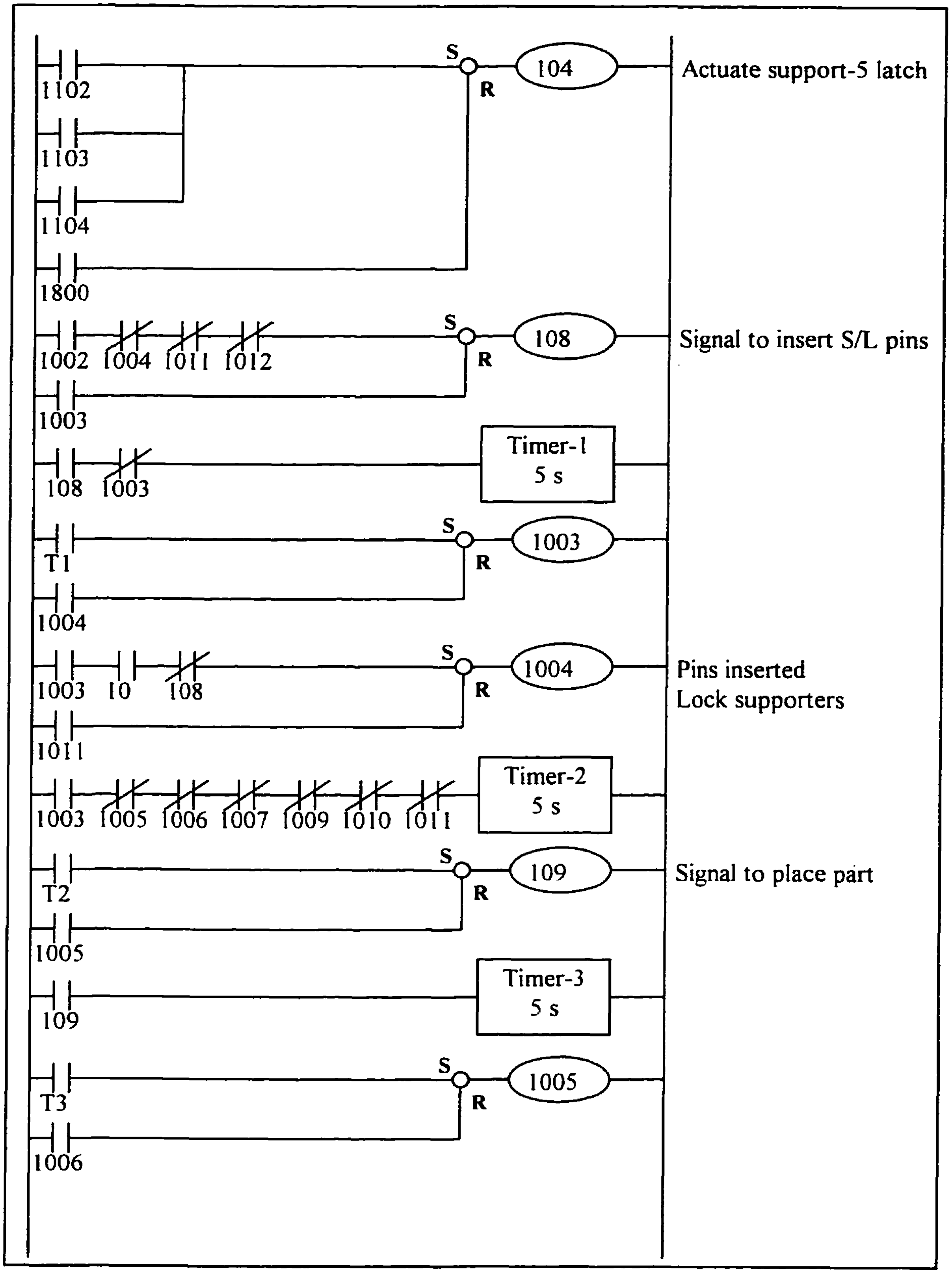


Figure 4.9(e): PLC logic to control the fixture

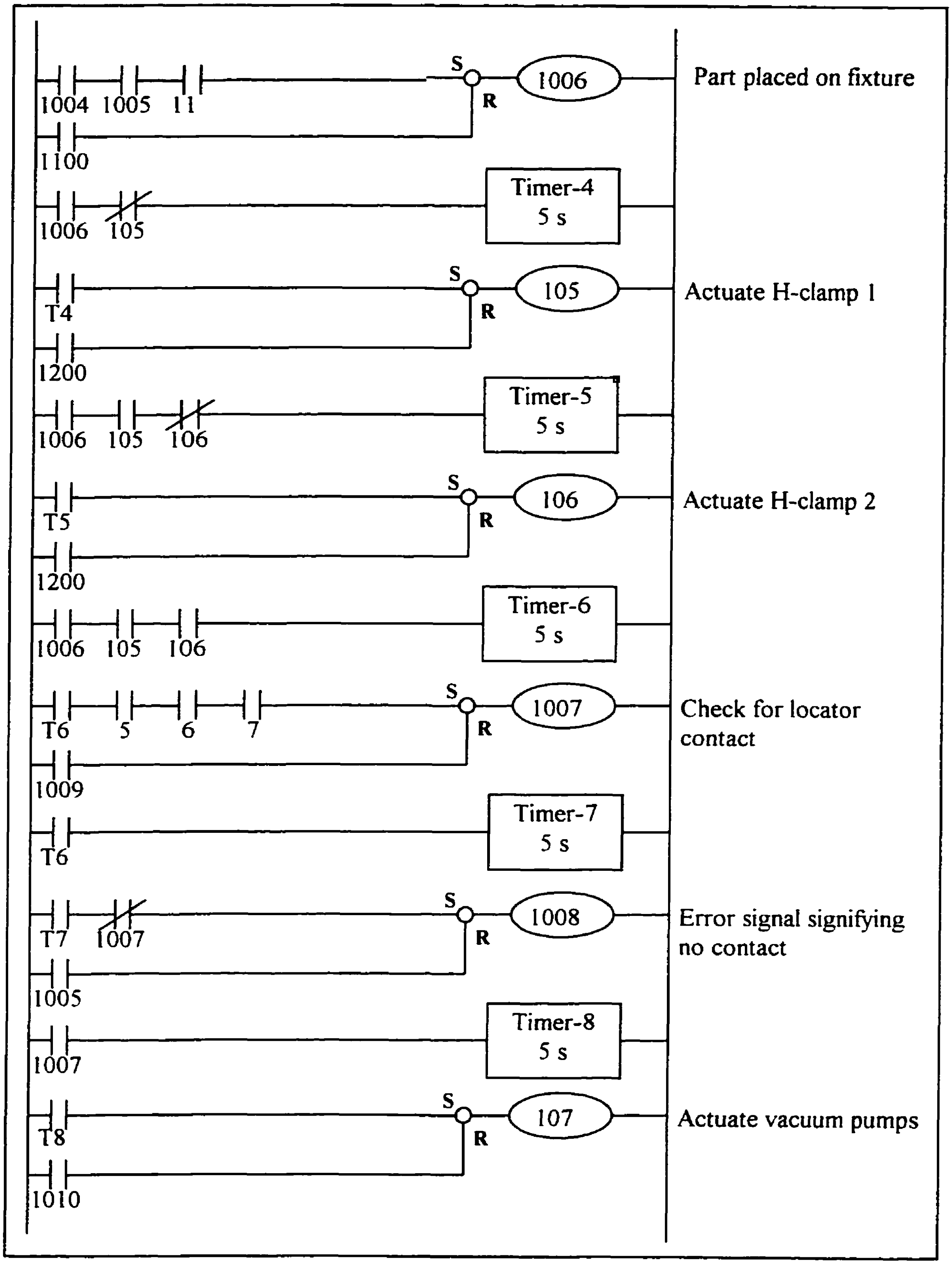


Figure 4.9(f): PLC logic to control the fixture

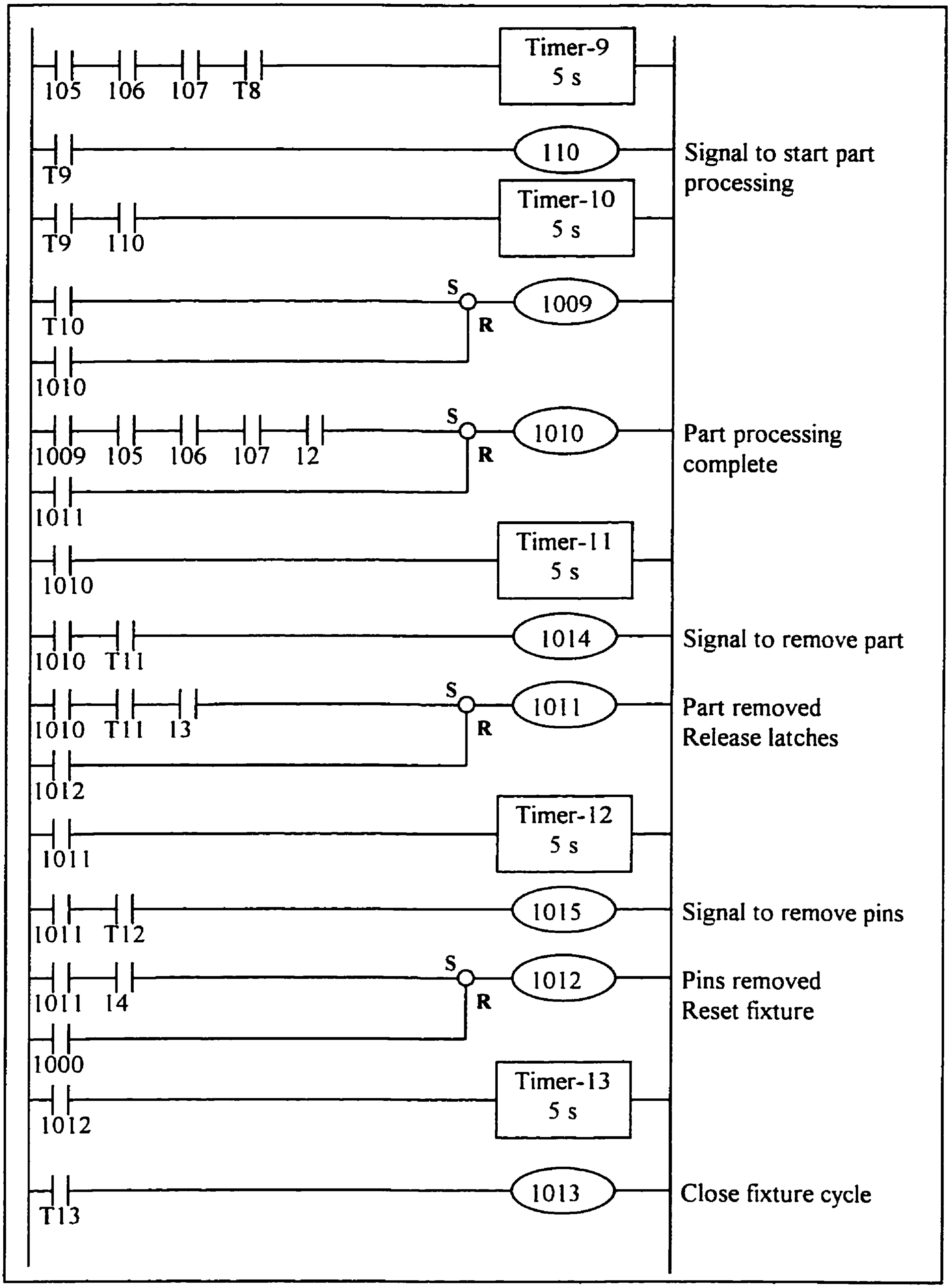


Figure 4.9(g): PLC logic to control the fixture

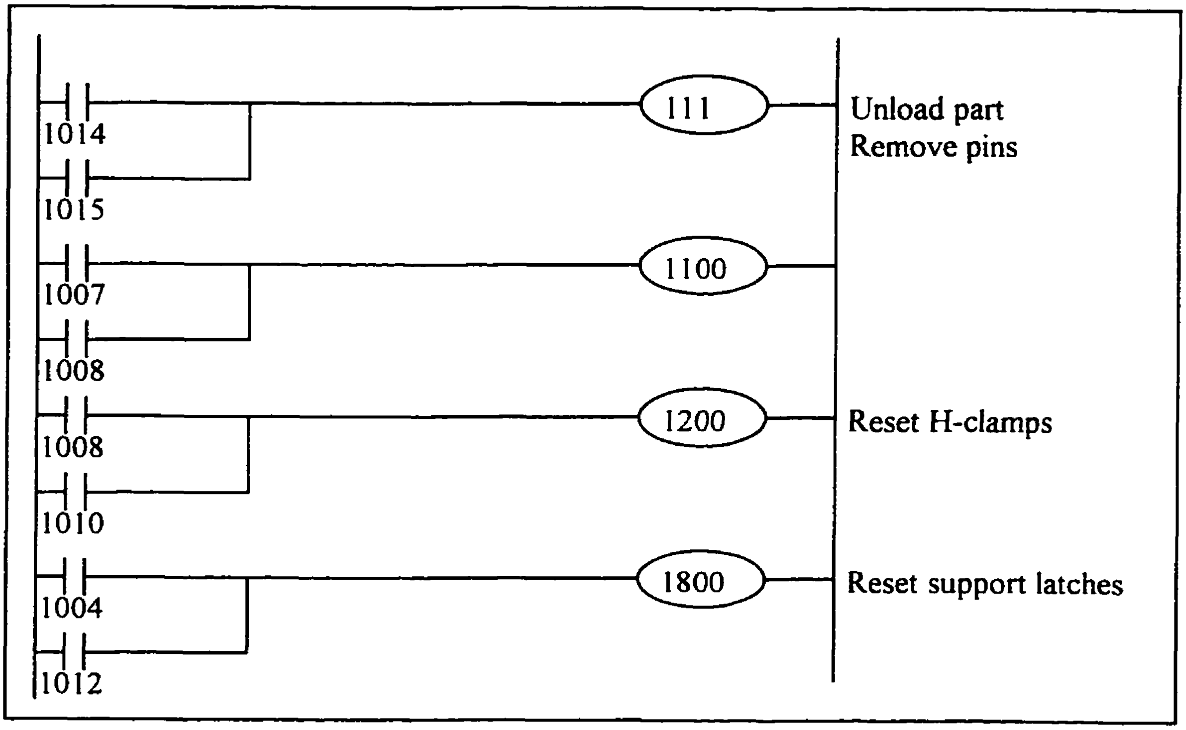


Figure 4.9(h): PLC logic to control the fixture

The modular concept is implemented in the control logic program by segmenting the program functionally. Inputs 1 through 4 are dedicated to part identification. The internal registers 1801 through 1804 are used to store the part identification number in the memory of the PLC. A part is identified from the status of these internal registers. The internal registers 1101 through 1104, as well as 1201 through 1204, are used to identify side-A and side-B of the parts, respectively. The output registers 100 through 104 are used to store the information required to support all the parts. Outputs 100 through 104 are used to actuate the supporter pin latches based on a part's identification number. Inputs 5, 6 and 7 are used to detect the locator pin contacts. The 1000 series internal registers are used to store the process status of fixturing and deburring. Inputs 8 through 14 as well as outputs 108 through 112 are used to interface with the robot's controller.

The modular concept enables the user to modify the program to either change the fixturing configuration for an existing part or to fixture additional parts. The procedure required to modify the logic program to fixture an additional part is presented below.

1) The binary representation of a part's identification number (side A or B) should be stored in the 1800 series internal registers.
2) The part's ID (side-A) status of the 1800 series registers should be assigned to a new 1100 series register to identify the part's side-A.
3) The part's ID (side-B) status of the 1800 series registers should be assigned to a new 1200 series register to identify the part's side-B.
4) The new 1100 and 1200 series registers should be appended to the condition stack of the reset register, 1002, to reset the 1800 series registers after identifying the part.
5) The information required to support the part (sides A and B) should be appended to the condition stack of the output registers, 100 through 104, by using the new 1100 and 1200 series registers.

Although the control logic program is developed for only four parts, it can be extended for upto sixteen parts. The fixture system requires 9 supporter pins. Only 5 supporter pins are used in the control logic program because of the limited output capacity of the available PLC. Also, The fixture system requires 22 locator pins. Only 3 locator pins are used in the control logic program because of the limited output capacity of the available PLC. A PLC with 38 input and 18 output channels is required to fixture all eighty parts.

4.5.2 Overall cell control

The new cell comprises the FANUC-S12 robot controller, the fixture controller, the FANUC robot and the fixture system. The main tasks involved in the cell are (i) identifying the part, (ii) fixturing the part, (iii) selecting the appropriate tool from the tool rack, (iv) selecting and executing the appropriate path program and (v) signaling the operator about the process status.

The fixture configurations required for all the parts are stored in the memory of the fixture controller. The fixture controller is utilized to identify and fixture a given part. It also communicates the status of the fixturing process to the robot's controller. The fixture controller also ensures that the part is oriented properly on the fixture table.

The path programs for a given part are loaded into the memory of the robot's controller. A separate subprogram is employed to retrieve the appropriate tool from the tool rack. The robot's controller executes a part specific, main program that calls the appropriate path programs and the tool change subprogram, when necessary. This main program enables the robot's controller to communicate with both the operator and the fixture's controller in order to synchronize the tasks performed in the cell. Also, the main program enables the robot's controller to operate the air motor.

The tasks of the robot's controller have been implemented at BAL's research and development facility. The fixture controller tasks were tested at the CIM and Automation Laboratory which is located at the University of Manitoba.

CHAPTER-5 Results

A representative part with relatively complex features, the one shown earlier in Figures 4.8(a) and 4.8(b), was selected to test the robot aided, deburring operations as well as the automated fixturing system. The implementation was demonstrated successfully at BAL's premises. The following hardware items were utilized to assist the implementation.

1) A 900 RPM air motor was used to operate the string brushes.
2) A 2400 RPM air motor was used to operate the unitized wheels.
3) A constant force device, shown earlier in Figure 3.4, was used to provide compliance as well as a constant force of approximately 0.5 lbf to the deburring tools.
4) A quick tool changing mechanism was used to select the required tools without operator intervention.

The tool change mechanism comprised a male and a female component. The male component was attached permanently to the face plate of the robot's end effector. Each tool module was equipped with a female component in the tool change mechanism. The tool module also included an air motor and a deburring tool. These tool modules were arranged at predefined stations in a tool rack. A sensor was attached to the male component of the tool change mechanism in order to assist the robot in the proper loading and unloading of the tool module. A path program was generated by using the teach pendant in order for the robot to load as well as unload a tool module based on the specified tool station number. The required tool was loaded onto the robot's end effector by executing the tool change program with the appropriate tool station number as the argument. The digital input / output feature of the robot controller was utilized to control the tool change mechanism as well as to operate the air motor.

5.1 Deburring results

The representative part was processed in two stages namely, the preliminary stage and the final stage. In the preliminary stage, the sharp edges of the part were chamfered to approximately 0.03" in order to expedite the edge rounding process during the final stage. The following tools were used to perform the various deburring operations.

1) A 2" diameter, 8A course, EXL unitized wheel was used to chamfer the sharp edges in the preliminary stage.
2) A 2" diameter, 6A course, EXL unitized wheel was used to blend the rough surface as well as to chamfer the curved edges in the final stage.
3) Two 80 grit string brushes, 6" in diameter and having a 1.5" string length, were used to round the chamfered edges in the final stage. Also, these string brushes were used to deburr the lugs and tabs in the preliminary stage in order to enable safe handling of the part between the two stages.

4) A 1" diameter, 2A medium, EXL unitized wheel was used to blend the web surface's inside narrow pockets that could not be accessed by a 2" diameter tool in the final stage.

The preliminary and final deburring operations were performed on the representative part. The finished part was tested for edge roundness and surface roughness at BAL's quality control facility. The results showed that the edges were rounded with a radius ranging between 0.025" to 0.030". This value was well within BAL's radius requirement of 0.020" to 0.040". The surface roughness was measured to be within 90 microns. This value was also well within BAL's requirement of less than 120 microns. Consequently, the final result was classified as acceptable by BAL's quality control facility.

The Fanuc-S12 robot was programmed, by using the teach pendant, to deburr both sides of the representative part. Independent path programs were generated to operate each tool on each side of the part. Robot programming involves teaching several points along an edge or on a surface of a part that needs to be to deburred. The task of teaching these points with precision is time consuming initially. However, the taught positions can be stored in the robot's controller and they can be retrieved quickly for subsequent parts. The time required to program the robot to process both sides is presented in Table 5.1. The table represents the dedicated programming time only and excludes any recess time taken by the skilled programmer whilst programming the robot. The programming time is approximately proportional to the degree of complexity in a part's shape. For example it can be observed from the table that the time taken to program side-A is greater than that for side-B. This is because the representative part has relatively fewer complex features on side-B than on side-A. Table 5.1 also indicates that the total dedicated programming time is 18 hours and 25 minutes. Although this programming time seems high, it is a one time, labor investment. An alternative perspective is that an average programming time of approximately 14 minutes is needed per part for a production rate of 80 parts per year.

		Programming time (h:m)	
Tool used	**Part feature**	**Side-A**	**Side-B**
2A medium 1" diameter wheel	Nose pocket	00:15	----
6A medium 2" diameter disc	Web surface	02:55	02:40
8A coarse 2" diameter disc	Edges (Stage-1)	04:00	04:00
String Brush	Edge (Final stage)	02:35	02:00
Total		**09:45**	**08:40**

Table 5.1: Robot programming time

The time taken for the robot to process both sides of the part is presented in Table 5.2. The results indicate that 83 seconds are required. This time includes processing in both the preliminary and final stages. The operator's assistance is required to load the part, select and start the appropriate path program, flip the part and unload the part when processing is completed. It is evident from the results that the operator's intervention to perform these tasks is one minute for the tool change plus three minutes to set a fixture and load the part. The total manual involvement is four minutes which is approximately 5% of the total processing time.

Operation	Processing time by robot (m:s)		
	Side-A	**Side-B**	**Total**
Edge Chamfer	12:30	10:00	22:30
Surface Blend	10:50	10:40	21:30
Edge Round	18:00	16:00	34:00
Tool Change	00:30	00:30	01:00
set fixture, load part	01:30	01:30	03:00
Program Start	00:30	00:30	01.00
Total / Sub total	**43:50**	**39:10**	**83:00**

Table 5.2: Processing time

The time taken presently to completely manually process the representative part is presented in Table 5.3. This information is obtained from shop order sheets for the last 27 parts that were processed manually at BAL. Operation (op 60), as indicated in Table 5.3, involves deburring the edges as well as drilling holes on the flanges. It is observed that approximately 30% of the Op 60 time is taken by the edge deburring operation. Operation (op 100), as indicated in Table 5.3, involves rounding the edges, blending the surface and the removal of kellering marks. Approximately 70% of the Op 100 time is utilized in the edge rounding and surface blending operations. Table 5.3 also indicates that an average of 2.83 man hours is spent on each represenatative part.

		Manual processing time based on recent history (man-hours)		
Date	Batch size	Edge deburr and drill (Op 60)	Surface blend and radius edges (Op 100)	Total time (30% of OP 60 + 60% of Op 100)
08/19/96	1	3.50	4.90	3.99
07/16/96	3	1.60	2.87	2.20
06/19/96	3	1.53	4.27	3.02
05/09/96	3	1.93	3.73	2.82
03/27/96	2	2.20	4.30	3.24
01/23/96	6	1.12	4.10	2.80
09/24/95	3	1.53	2.93	2.22
08/01/95	3	1.27	3.67	2.58
06/20/95	3	1.33	3.60	2.56
Average time		**1.78**	**3.82**	**2.83**

Table 5.3: Manual processing time based on recent history

The total time required for the robot to process the representative part is 1.38 hours. This number includes 0.07 hours of operator intervention but the operator could be involved in other tasks while the robot is processing the part. The time taken presently to manually process the part is 2.83 man hours. Thus, implementing the robot system could result in a saving of about 1.4 hours of processing time and 2.75 man hours of labor time for each representative part. However, the representative part tested is a relatively complex part. Hence, an average (conservative) saving of around 1 man hour per part is assumed for the robotic processing of all the 40 parts in the Boeing-777 part family. Considering the total number of parts produced annually and the labor cost, the saved man hour translates into an annual savings of about $112,000. The capital cost for a robotic cell is estimated to be $140,000. This includes the following components.

1) FANUC robot ($90,000.).
2) Fixturing and Tooling ($30,000.).
3) Safety system ($10,000.)

Based upon the above projected costs and benefits, an internal rate of return analysis, (IRR), was conducted by BAL. The estimated payback period is less than 2 years.

5.2 Fixturing results

Fixture components such as the locator pins with a sensory feedback capability, supporter units equipped with a vacuum suction clamp, supporter latch unit and the horizontal clamps were designed and machined at BAL. The performance of the fixture components were found to be effective. The design allowed the robot to insert these units at specified locations on the fixture table. Also, the fixture controller can automatically latch the supporter units, without operator interference.

The fixture component locations were selected strategically and the fixture system was demonstrated successfully. As a programmable logic controller was not available, the robot controller was utilized to simulate a PLC environment. The fixture system was implemented successfully to fixture the representative part whilst robotic processing. The logic program to control the fixture system was developed and demonstrated successfully at the CIM and Automation Laboratory of the University of Manitoba, Winnipeg. The digital input / output feature of the robot's controller was utilized to control the fixture. The corresponding schematic is shown in Figure 5.1. However, the robot's controller is not capable of performing boolean logic operations which can be quite restrictive. On the other hand, a complex control program can be implemented with ease by using a PLC. The cost of such a programmable logic controller is approximately $2,500.

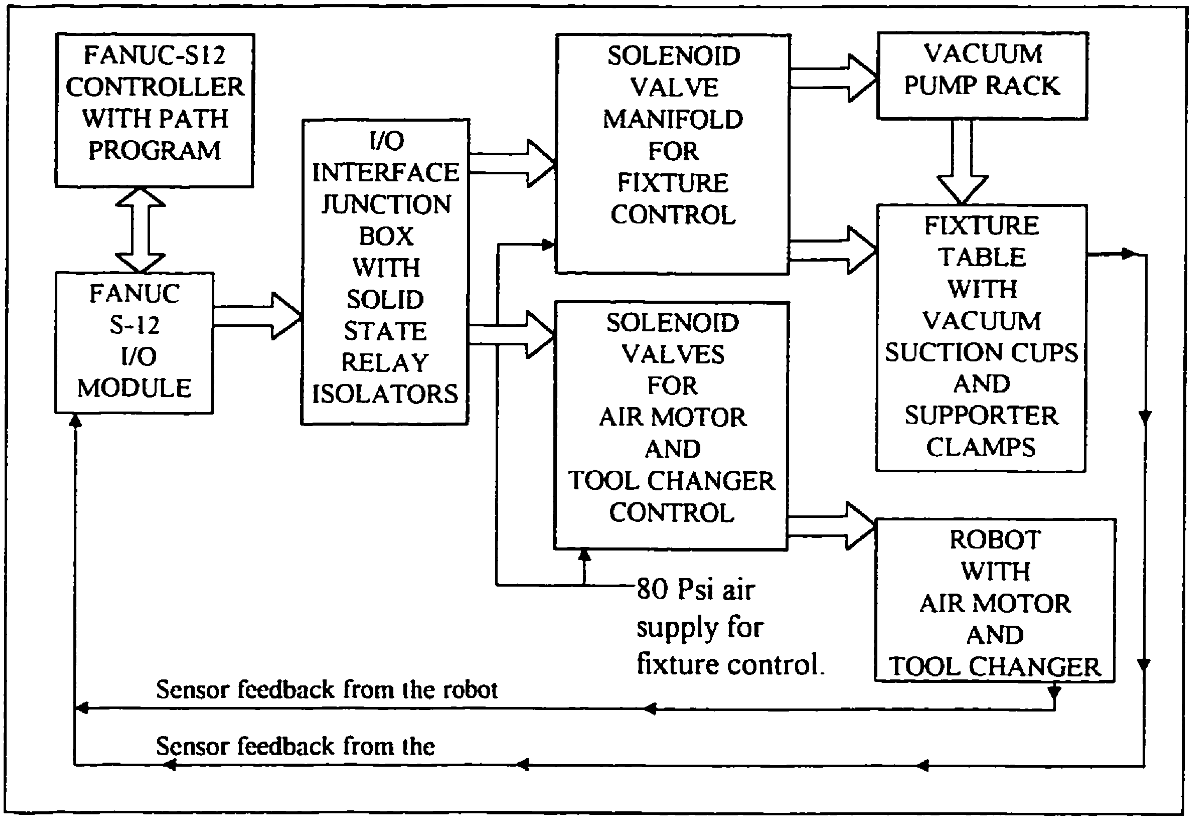


Figure 5.1: digital I/O interface of FANUC-S12

Chapter-6 Conclusions and Recommendations

6.1 Conclusions

The dual problems of robotic deburring and the related automated fixturing of Boeing-777 components have been addressed. The FANUC-S12 robot's performance was investigated and it was found to be suitable for deburring. The developed deburring methodology was tested successfully with the selection of appropriate deburring tools. Robotic deburring and surface blending was demonstrated by successfully processing a relatively complex, production part. An automated fixture system, based on a modular concept, was developed to fixture the Boeing-777 components in order to aid the robotic deburring. Special purpose fixture elements were designed and developed. Their functionality was demonstrated successfully. It was also proved that the system will result in a payback period of less than 2 years.

6.2 Recommendations

A force analysis, followed by an iterative process to determine the locations of the fixture components for a given workpiece, has been proposed. The methodology can be incorporated within the control software to automatically select these locations. This process was not completed due to time constraints. User friendly software can be developed to automatically configure a fixture for a given workpiece. Such software would utilize user information to query the geometrical model of the workpiece for clampable areas and then select the optimal clamping locations based on a stability analysis. User information would include the clamping force, deburring force, clamp dimensions, dowel hole spacing and no-access zones for a workpiece.

The present system utilizes the robot's controller to store all the necessary path programs and the main program for a given part. Many parts need many programs to be stored in the robot's controller memory. The use of a personal computer is recommended to store and retrieve the robot's path programs for all the parts that require deburring in the cell. The personal computer can also be employed to transfer the appropriate path programs to and from the robot's controller based on a part's identity number. The fixture configurations required by all the parts can be stored and retrieved from the personal computer to fully automate this process. An identification device, such as a bar code reader, can be used to reliably identify the parts. A programmable logic controller having an extended input / output capacity can be dedicated to efficiently control the fixture.

References

[1] A. J.C. Trappey and C.R. Liu, "A literature survey of fixture design automation", *The International Journal of Advanced Manufacturing Technology*, vol. 5, no. 3, p 240-255, 1990.

[2] B. Benhabib, K.C. Chan and M.Q. Dai, "A modular programmable fixturing system", *Journal of Engineering for Industry*, vol. 113, p 93-100, Feb. 1991.

[3] R.C. Brost and K.Y. Goldberg, "A complete algorithm for synthesizing modular fixtures for polygonal parts", *Proceedings - IEEE International Conference on Robotics and Automation*, pt 1, p 535-542, 1994.

[4] Y. Zhuang, K.Y. Goldberg and Y. Wong, "On the existence of Modular fixtures", *Proceedings - IEEE International Conference on Robotics and Automation*, pt 1, p 543-549, 1994.

[5] R.C. Brost and K.Y. Goldberg, "A complete algorithm for designing planar fixtures using modular components", *IEEE Transactions on Robotics and Automation*, vol. 12, no. 1, p 31-46, 1996.

[6] R.C. Brost and R.R. Peters, "Automatic design of 3-d fixtures and assembly pallets", *Proceedings - IEEE International Conference on Robotics and Automation*, vol. 1, p 495-502, 1996.

[7] A.S. Wallack, "Generic fixture design algorithms for minimal modular fixture toolkits", *Proceedings - IEEE International Conference on Robotics and Automation*, vol. 1, p 487-494, 1996.

[8] C. Liu, "A systematic conceptual design of modular fixtures", *The International Journal of Advanced Manufacturing Technology*, vol. 9, no. 4, p 217-224, 1994.

[9] B. Shirinzadeh, "Issues in the design of the reconfigurable fixture modules for robotic assembly", *Journal of Manufacturing Systems*, vol. 12, no. 1, p 1-14, 1993.

[10] B. Shirinzadeh and Y. Tie, "Experimental investigation of the performance of a reconfigurable fixturing system", *The International Journal of Advanced Manufacturing Technology*, vol. 10, no. 1, p 330-341, 1995.

[11] J. Ponce, "On planning immobilizing fixtures for three dimensional polyhedral parts", *Proceedings - IEEE International Conference on Robotics and Automation*, vol. 1, p 509-514, 1996.

[12] A. Willy, J.P. Sadler and R.D. Schraft, "Automated fixture design", *The International Journal of Advanced Manufacturing Technology*, vol. 10, no. 1, p 27-35, 1995.

[13] R.I.M. Young and R. Bell, "Fixturing strategies and geometric queries in setup planning", *International Journal of Production Research*, vol. 29, no. 3, p 537-550, 1991.

[14] A.J.C. Trappey and S. Matrubhutam, "Fixture configuration using projective geometry", *Journal of Manufacturing Systems*, vol. 12, no. 6, p 486-495, 1993.

[15] Z. Lin and C. Yang, "An expert system for fixturing design for face milling using modular fixture", *The International Journal of Advanced Manufacturing Technology*, vol. 10, no. 6, p 379-388, 1995.

[16] K.C. Chan and C.S. Lin, "Developement of a computer numerical control (CNC) modular fixture - machine design of a standard multifinger module" *The International Journal of Advanced Manufacturing Technology*, vol. 11, no. 1, p 18-26, 1996.

[17] J. Cabadaj, "Theory of computer aided fixture design", *Computers in Industry*, vol. 15, no. 1-2, p 141-147, 1990.

[18] M.J. Hockenberger and E.C. De meter, "The effect of machining fixture design parameters on workpiece displacement", *Manufacturing Review*, vol. 8, no. 1, p 22-32, 1995.

[19] K. Yu and K. Goldberg, "Fixture loading with sensor based motion plans", *Proceedings - IEEE International Symposium on Assembly and Task Planning*, p 362-367, 1995.

[20] R. Wagner, Y. Zhuang and K. Goldberg, "Fixturing faceted parts with seven modular struts", *Proceedings - IEEE International Symposium on Assembly and Task Planning*, p 133-139, 1995.

[21] K. Pennev and A.A.G. Requicha, "Fixture foolproofing for polygonal parts", *Proceedings - IEEE International Symposium on Assembly and Task Planning*, p 127-132, 1995.

[22] A.J.C. Trappey, C. Su and S. Huang, "Methodology for location and orientation of modular fixtures", *Manufacturing Science and Engineering*, ASME, vol. 64, p 333-342, 1993.

[23] N. Ramachandran, S.S. Pande and N. Ramakrishnan, "The role of deburring in manufacturing: A state-of-the-art survey", *Journal of Material Processing Technology*, vol. 44, p 1-13, 1994.

[24] Anon, "Robot deburring has block savings", *Machinery and Production Engineering*, vol. 149, no. 3805, p 22-25, 1991.

[25] G. Selinger, L. H. Hsieh, "Sensor aided programming and movement adaptation for robot guided deburring of castings", *Annals of the CIRP*, vol. 40, no. 1, p 487-490, 1991.

[26] G. De-Gol, "Robots for workpiece handling to stationary tools", *Assembly Automation*, vol. 15, no. 3, p 26-28, 1995.

[27] P. Cole, "Deburring with 3-dimensional abrasives", *Sheet Metal Industries*, vol. 65, no. 8, p 402, Aug., 1988.

Appendix A Evaluation of Fanuc-S12 Robot's Performance

The reliable performance of the robot aided deburring system depends on the performance of the robot. The suitability of the FANUC-S12 robot to deburr aircraft components is investigated here. The FANUC-S12 robot is a six degree of freedom, articulated robot that was acquired to edge deburr and surface finish Boeing-777 aircraft components. The objective is to determine the accuracy, repeatability and the backlash of this particular robot. The tests were carried out at Bristol's premises. The test methods and results are discussed below.

A.1 Test to Determine Accuracy

The robot can be taught to move the tool center point (TCP) between any two points in the work envelope with either a linear motion or an angular rotation. The coordinates of the points are generated by the robot's controller with respect to the robot's origin (i.e., home position). Coordinates can be obtained from the display unit of the robot's teach pendant. The distance between the two spatial points can be obtained mathematically. The difference between the actual distance moved by the TCP and the calculated distance determines the accuracy of the robot.

The experimental setup to determine the robot's accuracy is shown in Figure A1. A cylindrical rod was attached perpendicular to the face plate of the robot's end effector. The robot was positioned by using the teach pendant, such that the rod was held vertically.

This orientation was verified by using a bubble level indicator. Eight positions along a line, which was parallel to the robot's global X-axis, were programmed by using the robot's teach pendant. The robot was programmed to move along a single axis in order to simplify distance calculations between two TCP positions. A very precise laser range finder (LRF) with a resolution of 0.0001mm was used to measure the distance traveled by the rod along the line. Distances between the programmed points were obtained from the teach pendant display. These distances were stored in the LRF's memory. The LRF measured the distance traveled by the rod between any two (taught) positions and compared it with the corresponding value stored in its memory. The LRF output an error list that can be interpreted to determine the accuracy of the robot.

The measurement cycle comprised the end-effector's forward motion from the first position to the eighth position and the return motion back to the first position. The robot stopped at all the intermediate positions during the forward and return motions. In the first part of this experiment, the LRF monitor was initialized (to zero) at the beginning of each measurement cycle. Thus, the net error accumulated at the end of each cycle was eliminated. In the second part of this experiment, the LRF monitor was not initialized at the beginning of each measurement cycle. Thus, the net error was allowed to accumulate at the end of each cycle. The experiment was also performed along a line parallel to the robot's global Y axis.

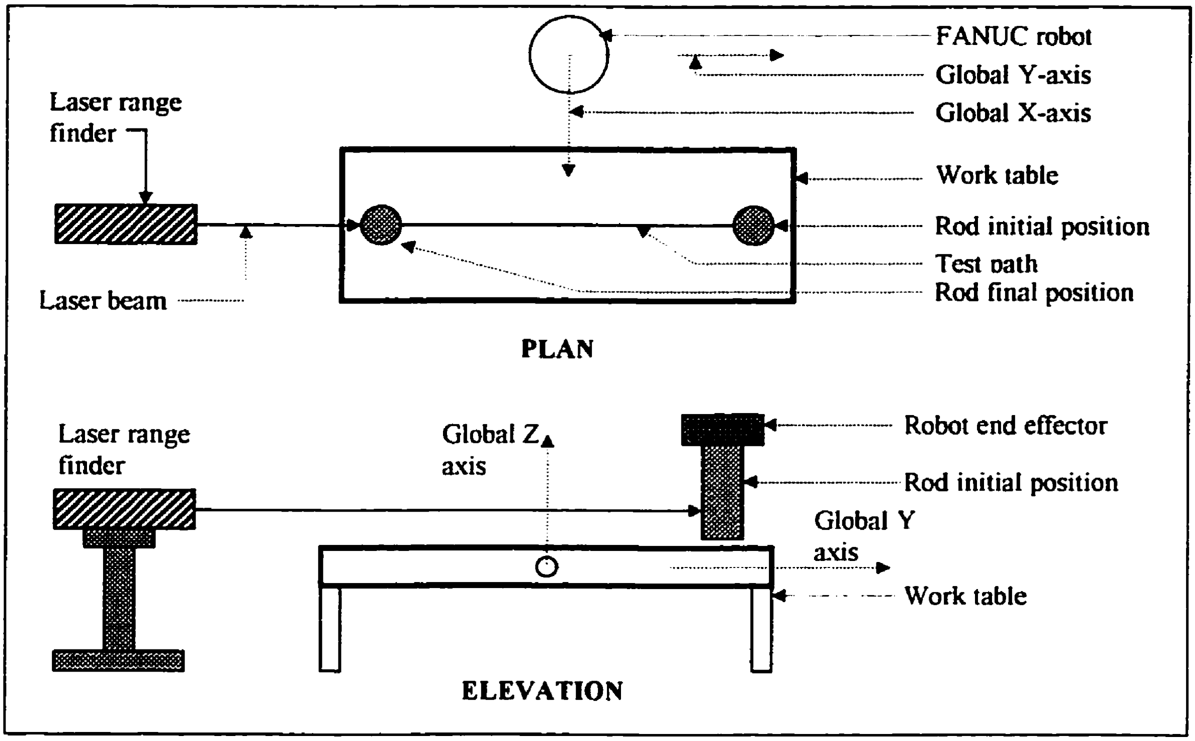


Figure A1: Experimental setup for accuracy test

The results from the experiment are presented in Tables A1 and A2. The maximum error was 0.1452 mm (0.00572") along the X-axis and 0.1270 mm (0.005") along the Y-axis. A machine tool with an accuracy of +/- 0.005" is generally not acceptable in an manufacturing environment. The results also revealed that the TCP reached a given position with an accuracy of within +/- 0.0005" in each measurement cycle. As the tools are used with a compliance device during deburring, this level of accuracy can be classified as acceptable.

Pos No	Position mm	LRF error reading ($X 10^{-4}$) mm									
		Readings with the error initialized after each cycle									
		Cycle-1		Cycle-2		Cycle-3		Cycle-4		Average	
		Fwd	Ret	Fwd	Ret	Fwd	Ret	Fwd	Ret	Fwd	Ret
1	0	-3	354	1	21	-6	11	-8	314	-4	175
2	67.811	2	-1041	-351	-1440	-354	-1427	-39	-1153	-186	-1265
3	167.780	1	-824	-382	-1387	-371	-1452	-38	-1041	-198	-1176
4	267.040	2	-684	-231	-1173	-327	-1235	-76	-861	-158	-988
5	366.639	331	-89	-321	-510	-314	-687	89	-385	-54	-417
6	466.015	45	-518	-335	-857	-384	-887	-50	-546	-181	-702
7	565.137	40	-552	-383	-1027	-296	-1053	19	-665	-155	-824
8	663.773	21	20	-294	-300	-343	-348	10	7	-152	-155
		Readings with the error not initialized after each cycle									
1	0	-1	12	11	18	19	24	20	32	12	22
2	67.811	-113	-1363	-290	-1391	-258	-1394	-299	-1383	-240	-1383
3	167.780	-327	-1291	-349	-1389	-348	-1194	-246	-1254	-318	-1307
4	267.040	-315	-1129	-347	-1120	-302	-1061	-320	-1105	-321	-1104
5	366.639	-71	-670	-27	-728	-239.	-659	-314	-697	-163	-689
6	466.015	-328	-850	-259	-791	-269	-801	-275	-782	-283	-806
7	565.137	-347	-970	-339	-969	-289	-983	-273	-1004	-312	-982
8	663.773	-299	-306	-311	-310	-315	-315	-276	-276	-300	302

Table A1: Results of accuracy test along X-axis

Pos No	Position mm	LRF error reading (X 10^{-4}) mm									
		Readings with the error initialized after each cycle									
		Cycle-1		Cycle-2		Cycle-3		Cycle-4		Average	
		Fwd	Ret	Fwd	Ret	Fwd	Ret	Fwd	Ret	Fwd	Ret
1	0	10	-80	-80	-120	10	100	90	50	7.5	-13
2	218.995	10	1160	70	1180	1120	1270	130	1230	333	1210
3	327.431	-100	750	80	830	0	900	70	890	-13	843
4	400.543	20	670	-20	650	50	700	60	650	28	668
5	460.339	-60	960	-30	960	20	1040	10	1020	-15	998
6	523.127	-30	930	-60	990	-20	990	50	950	-15	998
7	610.392	-40	920	-20	980	-70	970	40	980	-23	963
8	766.303	-40	1040	30	1030	10	1060	-40	1060	-10	1048
9	961.420	-10	840	10	840	50	820	-100	830	-13	833
10	1094.577	0	830	40	840	-40	890	-60	720	-15	820
11	1207.317	300	290	290	290	260	250	180	180	258	253
		Readings with the error not initialized after each cycle									
1	0	40	-230	-220	-190	-180	-240	-230	-250	-148	-228
2	218.995	-90	1040	-10	1050	-170	1100	-140	1080	-103	1068
3	327.431	-20	690	-50	600	-160	680	-60	710	-73	670
4	400.543	-80	560	-70	520	-110	510	-30	560	-73	538
5	460.339	-100	860	-90	860	-100	840	-180	830	-118	848
6	523.127	-160	870	-90	850	-90	860	-40	850	-95	858
7	610.392	-130	810	-130	870	-140	890	-110	890	-128	865
8	766.303	-60	890	-120	860	-160	880	-140	900	-120	883
9	961.420	-120	700	-130	640	-60	710	-110	760	-105	703
10	1094.577	-130	730	-220	800	-190	720	-130	660	-168	728
11	1207.317	130	130	150	90	180	180	40	40	125	110

Table A2: Results of accuracy test along Y-axis

A2 Test to Determine Repeatability

The positioning repeatability of the robot determines the quality of the parts produced. A robot with excellent repeatability is preferred in order to consistently produce quality parts. An experiment was conducted to determine the repeatability of the FANUC-S12 robot.

A spherical probe having a 0.5" diameter and a 1.0" long shank was attached to the face plate of the robot's end-effector, as shown in Figure A2. This probe was positioned initially at an arbitrarily selected position. Three linear dial gages were set firmly against the probe to measure the deviation in the probe's position along the X, Y and Z axis from this position. The dial gages used to measure the displacements along the X-axis and the Z-axis have a resolution of 0.001" per division. The dial gage used to measure the displacement along the Y-axis has a resolution of 0.0001" per division.

The robot was programmed to follow a complex path, starting from the initial position and returning to the same position in the same orientation. The complex path was chosen such that all the six axes of the robot were involved in the motion. This cycle was repeated ten times. The readings on the three dial gages were noted at the end of each cycle. The FANUC-S12 robot's brakes were engaged automatically whenever the robot idled for more than 40s. The TCP moved -0.005" along purely the global Z-axis whenever the robot's brakes were engaged. The experiment was conducted under a no load condition and the readings were taken both before and after the brakes engaged. The experiment was repeated under a load condition. As the payload of the FANUC-S12 robot is approximately 24 lb, a load of 14 lb was used in the latter experiment.

Results from the experiment are presented in Table A3. The dial gage readings are presented in divisions. It is observed from the results that the probe is displaced by -.005" along the Z axis whenever the brakes were engaged. This indicates that the robot is not executing any program during this period. Still, the robot returned accurately to the initial position in the subsequent cycles. This observation confirms that the robot's brakes have no effect on the robot's performance. The results also revealed that the probe returned to the starting position with an accuracy of within +/- 0.0005". This level of repeatability is fine for the deburring where compliant tools are employed. Therefore, it can be concluded that the FANUC-S12 robot has acceptable repeatability to be utilized in deburring.

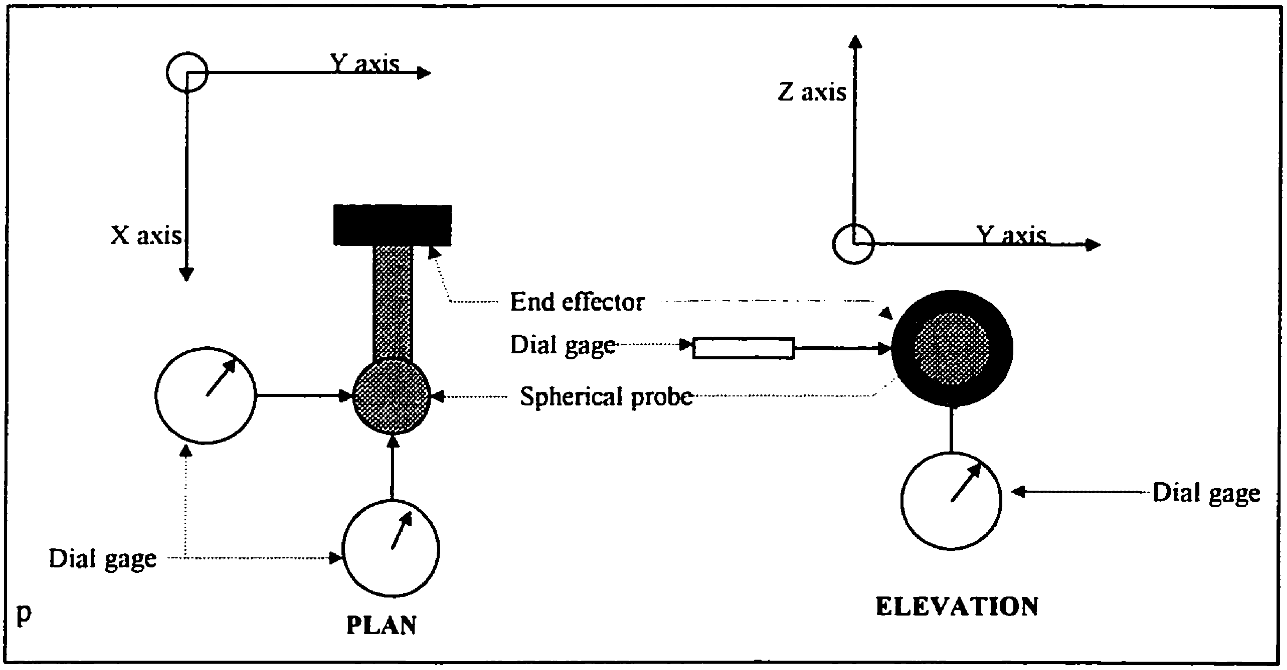


Figure A2: Experimental setup for repeatability test

Cycle no:	Dial gage reading before brakes			Dial gage reading after brakes		
	X-axis 0.001"/div	Y-axis 0.0001"/div	Z-axis 0.001"/div	X-axis 0.001"/div	Y-axis 0.0001"/div	Z-axis 0.001"/div
	No load					
1	0	0	0	0	4	5
2	0	-2	0	1	0	5
3	-1	0	0	0	2	5
4	-1	-	0	-1	0	5
5	-1	2	0	-1	4	5
6	-1	-1	0	-1	2	5
7	0	-1	0	1	2	5
8	0	5	0	0	5	5
9	0	2	0	0	4	5
10	0	2	0	0	4	5
	14 lb. Load					
1	0	0	0	0	0	5
2	0	-1	0	0	-2	5
3	0	0	0	-1	0	-4
4	0	-1	0	-1	-3	5
5	0	0	0	-1	2	5
6	0	0	0	-1	-1	-5
7	0	0	0	0	-1	0
8	0	-1	0	0	7	3
9	0	-1	0	0	2	5
1 0	0	0	0	0	2	4

Table A3: repeatability results

A3 Test to Determine Backlash

Backlash is caused by the mechanical play in a robot's joints, links and gear assemblies. A machine tool builder will generally provide the necessary backlash compensation in the control software. The backlash, if any, that is experienced at the TCP is the result of backlash present in all the joints and links. Such backlashes would appear only when the direction of motion is reversed. Structural play will arise, conversely, when the robot encounters an opposing force. The robot will typically experience a cutting force of about 0.5 to 3 lb in deburring. The deburring and surface finishing operations involve forward and reverse motions. This experiment was conducted to investigate the presence of backlash and the structural play in the robot.

The robot should be jogged in small increments against an opposing force. In the presence of structural play, the robot's joints will move but the TCP position will not change until the play is nullified. The difference between the TCP position when the TCP stops and the TCP position when the TCP starts a motion represents the play. The TCP position can be obtained from the display unit of the robot's teach pendant. The play can be measured by using a linear dial gage to monitor the end-effector's motion. The force required to cause the play can be measured by using a linear displacement force meter. Also, when the jog direction is reversed, the difference in the TCP position will indicate the robot's backlash.

The robot's end-effector was positioned in a given location. A linear displacement force meter was mounted firmly on the work table and it was oriented parallel to the X axis. This force meter was used to apply the necessary opposing force. The force meter has a range of 0 to 30 lbf for a linear displacement of 0 to 10mm. A linear dial gage was used to measure the end-effector's displacement along the global X-axis. The dial gage had a resolution of 0.001" per division. The manipulator was jogged along the global X-axis in increments of approximately 0.05mm and the force as well as the dial gage readings were taken at the end of each motion. The experiment was repeated to measure the backlash along the global Y-axis.

The results along the global X-axis and Y-axis are shown in Table A4. The dial gage readings are presented in divisions. It is observed from the Table that there was a 2 division increase in the gage reading for every 0.05mm increase in the TCP position. It is also found that the increment in the gage reading decreased when the opposing force reached 4.25 lbf, even though the teach pendant display showed a constant increment in the position of the TCP. This discrepency indicated the presence of structural play. It was also observed that, when the jog direction was reversed, the TCP position changed. However, the dial gage showed a constant value. The corresponding result revealed that the robot had a structural play of 0.002" at 4.25 lbf of opposing force. The results also revealed that the manipulator had a backlash of 0.001".

The cutting forces generated during deburring are less than 3 lbf. Hence, the play will not show up during normal deburring. Also, the backlash was found to be 0.001" against an opposing force of 4.25 lbf. It was concluded that the FANUC-S12 robot has acceptable levels of backlash and play.

Sl Number	TP Reading mm	Force lb	Gage x 10^{-3} in.	Sl No	TP Reading mm	Force lb	Gage x 10^{-3} in.
1	1251.198	0	0	15	1251.898	4.0	26
2	1251.248	0.25	2	16	1251.948	4.25	28
3	1251.298	.5	3.5	17	1251.998	4.25	30
4	1251.348	1	5	18	1251.048	4.25	31
5	1251.398	1.25	6.5	19	1251.098	4.25	33
6	1251.448	1.75	8	20	1251.148	4.25	34
7	1251.498	2.0	10	21	1251.198	4.5	34
8	1251.548	2.25	12	22	1251.248	4.75	37
9	1251.598	2.5	14	23	1251.198	4.5	37
10	1251.648	2.75	16	24	1251.148	4.25	36
11	1251.698	3.0	18	25	1251.098	3.75	34.5
12	1251.748	3.25	20	26	1251.048	3.25	32
13	1251.798	3.5	22	27	1251.998	3	31
14	1251.848	3.75	24	28	1251.948	2.5	29
1	-364.855	0	0	12	-365.105	2	26
2	-364.905	0.25	2	13	-365.055	2	28
3	-364.955	0.5	3.5	14	-365.005	2	30
4	-365.005	0.5	5	15	-364.955	1.75	31
5	-365.055	1	6.5	16	-364.905	1.5	33
6	-365.105	1.25	8	17	-364.855	1.25	34
7	-365.155	1.5	10	18	-364.805	1	34
8	-365.205	1.75	12	19	-364.755	0.75	37
9	-365.255	2	14	20	-364.705	0.5	37
10	-365.205	2	16	21	-364.655	0.25	36
11	-365.155	2	18	22	-364.605	0	34.5

Table A4: Backlash results

Appendix-B Evaluation of Fanuc-S12 Frame Shift Capability

The FANUC-S12 controller offers five independent user frames. Each user frame is set by providing the position of the user frame's origin and the user frame's orientation with respect to the robot's global frame. A path program can be generated for the robot by teaching it the position and orientation of the required points along the desired path, with respect either to the robot's global frame or to any of the predefined user frames. A path program generated in one frame cannot be executed in another frame. However, the FANUC-S12 controller allows its users to redefine a user frame an infinite number of times and still be able to execute a previously generated program in a redefined frame. This feature provides the ability to shift the user frame from its current location to any desired location within the robot's work envelope and avoid the tedious task of reprogramming the robot's activities after each frame shift. A test was designed to study the repeatability of the robot when it is operated in a shifted frame. The user frame can be defined by using the three point method. This method used an origin as well as a point on the X axis and a point in the X-Y plane to determine the user frame's position and orientation with respect to the robot's global frame. The test was undertaken in two steps. In the first step, a user frame, A0, was defined with the point in the X-Y plane furthest from the origin. In the last step, a user frame, B0, was defined with the point in the X-Y plane closest to the origin. The experiment and results are discussed in the following sections.

B1 Experimental Setup

Three modular base plates were combined, as shown in Figure B1, to form the test platform. The base plates were rectangular steel plates with a lattice of holes that are spaced evenly at 1.25" +/-0.001". The test platform contained 48 holes along its length and 16 holes along its width. These holes were a combination of dowel and tapped holes, arranged alternatively. The X-Y coordinates of the insertion points of the dowel pins were given relative to the hole positions on the base plate. A sharp needle of known dimensions was attached to the robot's end effector. The direct entry method was used to set up the tool frame for the needle attachment. Three identical dowel pins were used to define the user frame parameters. Each dowel pin was equipped with a conical head having an included angle of 90 degrees. A rectangular aluminum block was used as the test piece. The aluminum block was equipped with two dowel pins for precise mounting on the base plate. A set of hairline crosses were marked on the test block and the intersection points were taken as the test points. The needle attachment, aluminum block and the three dowel pins were machined at BAL's tool build facility.

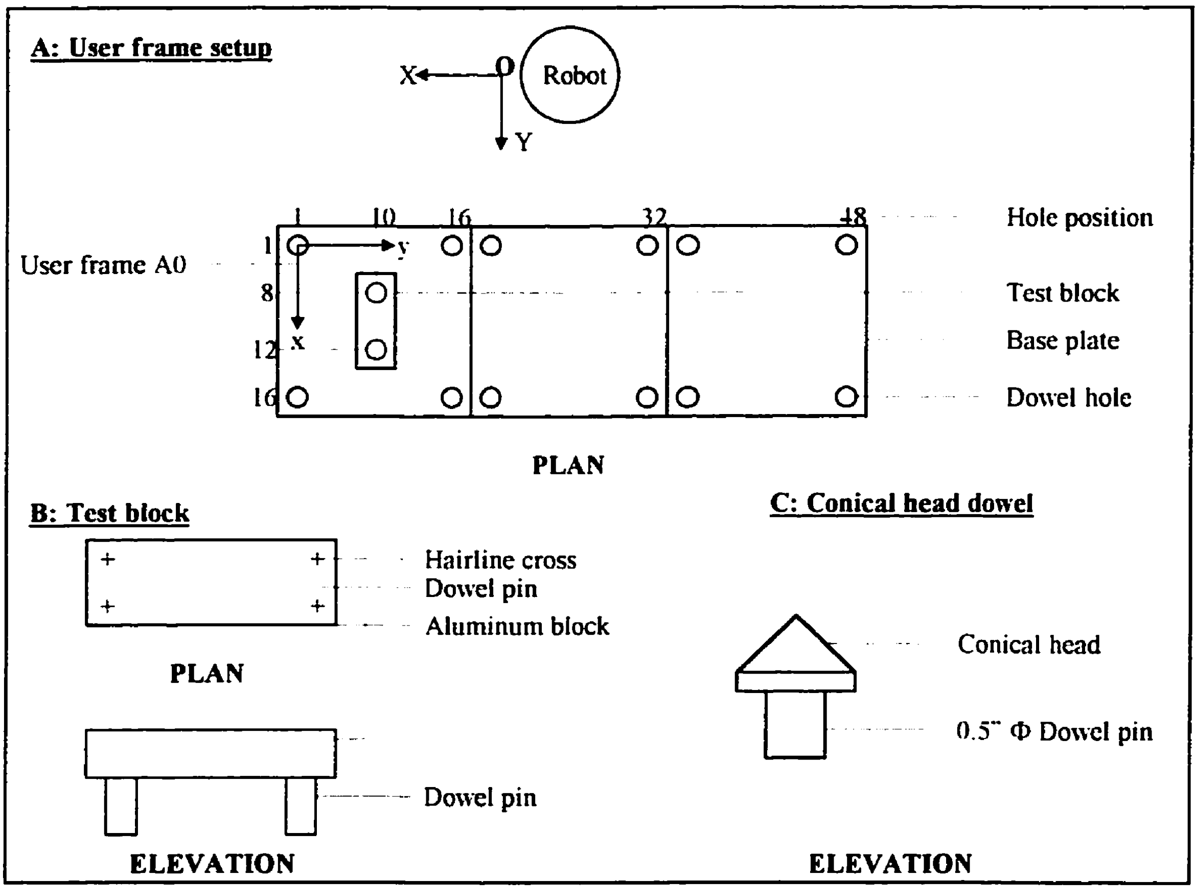


Figure B1: Experimental setup to find FANUC-S12 Frame shift

B2 Experimental Procedure

The user-frame, A0, was set up initially by using the three point method. See Figure B1. The user frame's origin was defined by inserting the first dowel pin in hole location (1,1). The direction vector along the X axis was defined by inserting the second dowel pin in hole (16,1). The positive quadrant of the X-Y plane was defined by inserting the third dowel pin in hole (8,48). The aluminum block was mounted on the base plate with its dowel pins located in holes (8,10) and (12,10). A path program was generated, by using the teach pendant, to require the robot to touch the test points on the aluminum block with the needle tip. This program was executed several times to ensure the repeatability of the robot in the user frame A0. The user frame was shifted to five different locations, labeled, A1, A2, A3, A4 and A5. The locations of the dowel holes used to define frames A1 through A5 are presented in Table B1. The position vector of the origins of the above mentioned user frames are presented in Table B2, with respect to the robot's global coordinates.

	User frame Dowel pin location			Test block Dowel pin location	
Frame	**Origin**	**X-direction**	**X-Y Plane**	**PIN 1**	**PIN 2**
A0	**1, 1**	**15, 1**	**8, 48**	**8, 10**	**12, 10**
A1	**2, 2**	**16, 2**	**14, 16**	**9, 11**	**13, 11**
A2	**3, 3**	**15, 3**	**16, 16**	**10, 12**	**14, 12**
A3	**3, 17**	**15, 17**	**16, 32**	**10, 26**	**14, 26**
A4	**3, 23**	**15, 23**	**16, 32**	**10, 32**	**14, 32**
A5	**1, 33**	**15, 33**	**13, 39**	**8, 42**	**12, 42**

Table B1: Origin of user frame locations on the fixture table

Frame	User frame position vector of origin					
	X (mm)	Y (mm)	Z (mm)	W(deg)	P (deg)	R (deg)
A0	664.9	888.6	-308.0	0	0.6	89.7
A1	633.5	920.2	-307.9	0.2	0.6	89.8
A2	602.1	951.4	-308.0	0.2	0.6	89.8
A3	161.2	948.0	-305.9	0	0.7	90.0
A4	-26.8	947.3	-305.7	0	0.7	90.2
A5	-340.2	883.7	-305.6	-0.1	0.6	90.4

Table B2: Origin coordinates of user frame

The path program was executed, in single steps, in each of the user frames. The position vector of the needle tip, with respect to the respective user frame was noted from the robot's teach pendant diplay whilst touching each test point. The data are shown in Table B3. The deviation of the needle tip's position at each test point, in the user frames A1 to A5, from the corresponding test point position in the user frame A0 was determined as shown in Table B4. These deviations represent the positional errors whose magnitudes determine the suitability of the robot's frame shift feature in deburring.

A new frame, B0, was set up as the initial user frame. The path program, as mentioned earlier, was generated in frame B0 by using the teach pendant. This program was executed several times to ensure the repeatability of the robot in the user frame B0. Then this user frame was shifted to four different locations namely, B1, B2, B3 and B4. The locations of the dowel holes used to define these user frames are presented in Table B5. The position vector of the origins of the user frames, with respect to the robot's global coordinates, are presented in Table B6. The previously described procedure was repeated in the user frames B1 through B4. The position vectors of the needle tip, with respect to the user frames are shown in Table B7. The deviations of the needle tip's position at each test point are given in Table B8.

It can be observed from Tables B4 and B8 that the maximum positional deviation along the X, Y and Z axes are -7.563mm, 1.161mm and 2.16mm respectively. The results also reveal that the magnitude of deviation increased when the user frame was shifted further from the initial frame. Hence, the deviation is not consistent with each frame shift. The position errors observed are not acceptable for deburring. Hence, it can be concluded that the frame shift feature of the employed FANUC-S12 robot is not suitable for deburring.

User frame	Test point	Tip position of needle w.r.t. user frame					
		X (mm)	Y (mm)	Z (mm)	W (deg)	P (deg)	R (deg)
A0	1	184.370	256.680	18.183	-179.233	-0.226	-50.504
	2	392.973	268.875	18.037	-179.233	-0.226	-50.504
	3	184.115	307.917	18.414	-179.234	-0.228	-50.507
A1	1	184.604	256.575	16.829	-179.234	-0.226	-50.504
	2	393.328	268.871	16.645	-179.234	-0.227	-50.504
	3	184.481	308.262	16.824	-179.234	-0.228	-50.507
A2	1	184.935	256.727	16.789	-179.234	-0.226	-50.504
	2	393.938	268.874	16.744	-179.233	-0.226	-50.505
	3	184.832	308.114	16.821	-179.235	-0.228	-50.507
A3	1	187.222	255.603	16.596	-179.234	-0.226	-50.504
	2	396.348	267.953	16.829	-179.234	-0.226	-50.504
	3	187.747	306.756	16.562	-179.234	-0.226	-50.507
A4	1	188.788	255.611	16.360	-179.234	-0.226	-50.504
	2	397.947	267.715	16.596	-179.233	-0.226	-50.504
	3	189.535	306.891	16.254	-179.234	-0.227	-50.507
A5	1	190.631	256.361	16.045	-179.234	-0.226	-50.504
	2	399.397	268.484	16.393	-179.233	-0.226	-50.504
	3	191.678	307.870	16.953	-179.234	-0.227	-50.507

Table B3: Tip position vector in user frame

Test point	Frame	Position error					
		X (mm)	Y (mm)	Z (mm)	W (deg)	P (deg)	R (deg)
1	A0	0	0	0	0	0	0
	A1	-0.234	0.105	1.354	0.001	0	0
	A2	-0.565	-0.047	1.394	0.001	0	0
	A3	-2.852	1.077	1.587	0.001	0	0
	A4	-4.418	1.069	1.823	0.001	0	0
	A5	-6.261	0.319	2.138	0.001	0	0
2	A0	0	0	0	0	0	0
	A1	-0.355	0.004	1.392	0.001	0.001	0
	A2	-0.965	0.001	1.293	0	0	0.001
	A3	-3.375	0.922	1.208	0.001	0	0
	A4	-4.974	1.160	1.441	0	0	0
	A5	-6.424	0.391	1.644	0	0	0
3	A0	0	0	0	0	0	0
	A1	-0.366	-0.345	1.590	0	0	0
	A2	-0.717	-0.197	1.593	0.001	0	0
	A3	-3.632	1.161	1.852	0	-0.002	0
	A4	-5.420	1.026	2.160	0	-0.001	0
	A5	-7.563	0.047	1.461	0	-0.001	0

Table B4: Position errors

	Dowel pin location				
	User frame			Test block	
Frame	Origin	X-direction	X-Y plane	Pin 1	Pin 2
B0	1, 1	15, 1	10, 16	8, 10	12, 10
B1	2, 2	16, 2	16, 16	9, 11	13, 11
B2	3, 3	15, 3	16, 16	10, 12	14, 12
B3	2, 2	16, 2	16, 16	9, 11	13, 11
B4	3, 3	15, 3	16, 16	10, 12	14, 12

Table B5: dowel pin locations on the fixture table in user frame

	User frame Position vector of origin					
Frame	X (mm)	Y (mm)	Z (mm)	W(deg)	P (deg)	R (deg)
B0	665.2	888.6	-308.0	0.2	0.5	89.8
B1	633.7	920.0	-308.0	0.2	0.5	89.8
B2	602.2	951.5	-308.1	0.2	0.5	89.8
B3	633.6	920.1	-308.0	0.2	0.5	89.8
B4	602.0	951.6	-308.1	0.2	0.5	89.8

Table B6: Origin locations on the fixture table

User frame	Test point	Tip position needle w.r.t. user frame					
		X (mm)	Y (mm)	Z (mm)	W (deg)	P (deg)	R (deg)
B0	1	184.782	256.942	16.974	-179.234	-0.226	-50.504
	2	393.327	269.151	16.694	-179.234	-0.226	-50.504
	3	184.356	308.347	16.935	-179.234	-0.227	-50.507
B1	1	185.022	256.951	16.978	-179.234	-0.226	-50.504
	2	393.577	269.154	16.697	-179.234	-0.226	-50.504
	3	184.721	308.351	16.938	-179.234	-0.227	-50.507
B2	1	185.184	256.842	16.854	-179.234	-0.226	-50.504
	2	394.079	268.654	16.754	-179.234	-0.226	-50.505
	3	184.857	308.049	16.892	-179.234	-0.227	-50.507
B3	1	185.017	256.948	16.977	-179.234	-0.226	-50.504
	2	393.569	269.151	16.692	-179.234	-0.226	-50.504
	3	184.714	308.347	16.933	-179.234	-0.226	-50.507
B4	1	185.132	256.848	16.804	-179.234	-0.227	-50.504
	2	393.779	268.703	16.702	-179.234	-0.226	-50.505
	3	184.848	307.898	16.841	-179.234	-0.227	-50.507

Table B7: Test locations in user frame

Test point	Frame	Position error					
		X (mm)	Y (mm)	Z (mm)	W (deg)	P (deg)	R (deg)
1	B0	0	0	0	0	0	0
	B1	-0.24	-0.009	-0.004	0	0	0
	B2	-0.402	0.100	0.120	0	0	0
	B3	-0.235	-0.006	-0.003	0	0	0
	B4	-0.350	0.094	0.170	0	0.001	0
2	B0	0	0	0	0	0	0
	B1	-0.250	-0.003	-0.003	0	0	0
	B2	-0.752	0.497	-0.060	0	0	0.001
	B3	-0.242	0	0.002	0	0	0
	B4	-0.452	0.448	-0.008	0	0	0.001
3	B0	0	0	0	0	0	0
	B1	-0.365	-0.004	-0.003	0	0	0
	B2	-0.501	0.298	0.043	0	0	0
	B3	-0.358	0	0.002	0	-0.001	0
	B4	-0.492	0.449	0.094	0	0	0

Table B8: Positional errors

Appendix C Computation of Clamping Locations

An example calculation for computing the clamping locations, by using equations (4.1) through (4.6), for the representative part shown in Figure C1, is presented. The deburring force generated by a cylindrical disc on the part's edge will range from 0.5 lbf to 1.0 lbf. The deburring force generated by a string brush on the part's edge will range from 1.0 lbf to 3.0 lbf. As the string brush generates a larger force than the cylindrical disc, this force (3.0 lbf) is considered in the computations to determine the clamping locations.

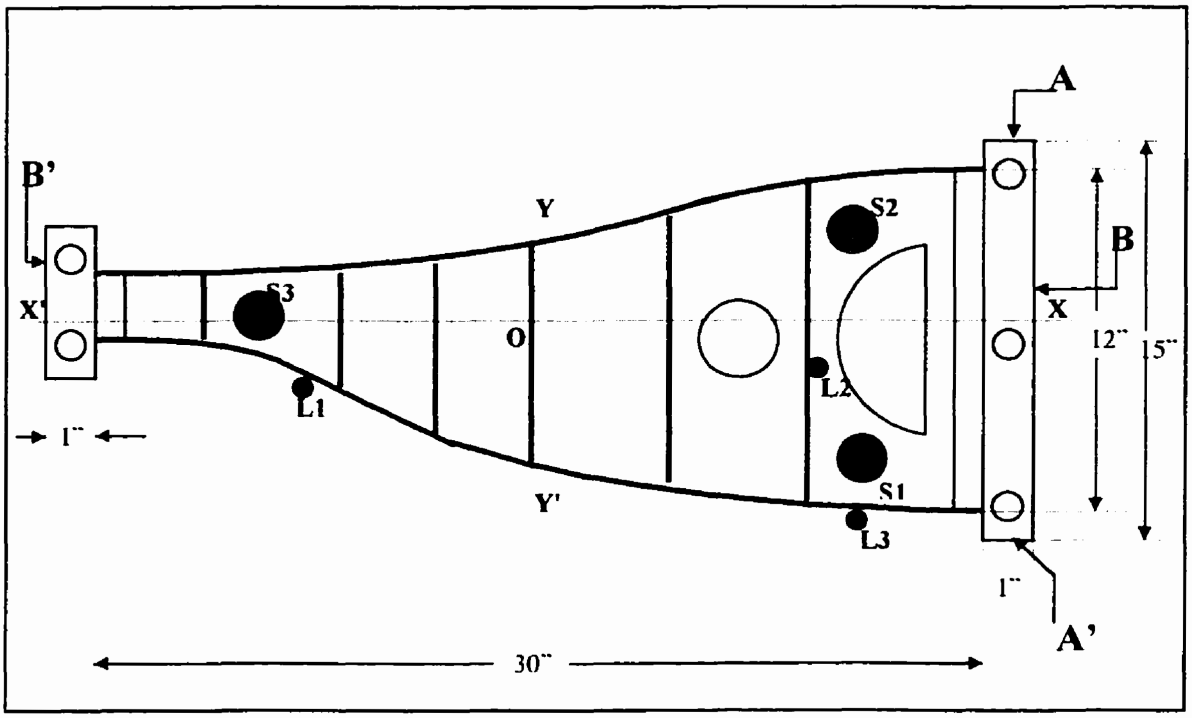


Figure C1: Part for computation of clamping locations

The part, as shown in Figure C1, is 30" long and 12" wide. The lug attached to the wider side of the part is 15" wide. Axes X-X' and Y-Y', as shown in Figure C1, are assumed to pass through the part's center of mass. The vertical component of the deburring force at points **A** and **A'** will produce the maximum moments about the X-X' axis. The vertical component of the deburring force at points **B** and **B'** will produce the maximum moments about the Y-Y' axis. The horizontal component of the deburring force at points **A** and **A'** will produce the maximum moments about the Z axis. The objective here is to determine the clamp location nearest to these axes that would balance the corresponding moments sufficiently.

Moment about X-axis:

Clamping force provided by suction cup:	16.4 lbf.
Deburring force produced by string brush:	3 lbf. max.
Distance **O-A**:	7"
Distance **O-A'**:	8"
Moment about axis X-X' due to force at point **A**	= **21.0 lbf-in**
Clamping distance below X axis	= **1.28"**
Moment about axis X-X' due to force at point **A'**	=**24.0 lbf-in**
Clamping distance above X axis	= **1.46"**

The suction clamp should be located at least **1.28"** below the **X-X'** axis in order to balance the moment generated by the deburring force at point **A**. Also, the suction clamp should be located at least **1.46"** above the **X-X'** axis in order to balance the moment generated by the deburring force at point **A'**.

Moment about Y-axis:

Distance **O-B**: 15"

Distance **O-B'**: 15"

Moment about axis Y-Y' due to force at point **B or B'** = **45.0 lbf-in**.

Clamping distance to the left or right of Y axis = **2.74"**

The suction clamp should be located at least **2.74"** to the left of the **Y-Y'** axis in order to balance the moment generated by the deburring force at point **B**. Also, the suction clamp should be located at least **2.74"** to the right of the **Y-Y'** axis in order to balance the moment generated by the deburring force at point **B'**.

Moment about Z-axis:

Slide resistance force provided by suction cup: =**8.8 lbf.**

Distance **O-B** or **O-B'**: =**15"**

Moment about axis **Z** due to force at point **A or A'** = **45.0 lbf-in**

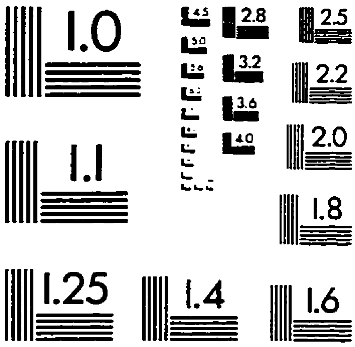
Total slide resistance force due to 3 clamps = **26.4 lbf.**

Clamping distance form Z axis = **1.74"**

Each suction clamp should be located at least 1.74" about the point **O** (Z axis) in order to balance the moment generated by the deburring force at point **A or A'**.

In order to achieve maximum stability, locations S1, S2 and S3 are determined for clamping the representative part. The points S1 and S2 are 5" apart and they are located 2.5" above and below the X-X' axis. They are also located about 10" to the right of the Y-Y' axis. The location S1 is located about 10" to the left of the Y-Y' axis.

IMAGE EVALUATION
TEST TARGET (QA-3)



150mm

6″

APPLIED IMAGE, Inc
1653 East Main Street
Rochester, NY 14609 USA
Phone: 716/482-0300
Fax: 716/288-5989