AN INDUSTRIAL PALLETIZING SYSTEM FOR INDUSTRIAL ROBOTS

by

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Thesis submitted to the Faculty of

the Virginia Polytechnic Institute and State University

in partial fulfillment of the requirements of the degree of

Master of Science

in

Industrial Engineering and Operations Research

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November 1985

Blacksburg, Virginia

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(Abstract)

A study was conducted to set up an automated system for the use of industrial robots in frequently changing palletizing applications. The system consists of an industrial robot (IBM Manufacturing System 7545), an IBM PC, a gripper carousel storage system, a quick change mechanism, and a robot gripper. The system is set up to enable a minimum of operator intervention. Hardware aspects (quick change mechanism and gripper storage) as well as dynamic software generation for different palletizing applications were considered in the research project.

The research effort involved both software and hardware developments. A FORTRAN program was developed to generate pallet patterns based on dynamic input of package and platform parameters. The geometric pattern was then used to create an

appropriate AML/E program to drive the robot through the desired motion sequence. This program was then compiled and downloaded to the robot. Hardware aspects of the research were focused on the development of a system to permit dynamic changing of end of arm tooling. This included development of a quick change mechanism and a gripper carousel storage system. The quick change mechanism included interfaces for electronic signals, air and vacuum lines. A vacuum gripper was also designed for package handling.

Acknowledement

The author wishes to express hearty gratitudes to his chairman, Dr. Michael P. Deisenroth for his invaluable guidance, support, and patience; to Dr. Marilyn S. Jones and Dr. Said W. Zewari for their recourseful ideas and advice.

Thanks are also due to Keith Wright and Bart Moore of the IEOR Machine Tool Laboratory at Virginia Tech for their supporting input in machining and assembling the research equipment.

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Chapter I

INTRODUCTION

The purpose of this chapter is to present to the reader basic material in robot technology and industrial palletizing applications. E. Grab [6] points out that the changing competitive conditions in industry today require new technologies to play a more important role in production and storage processes as compared with the situation of the last decade. Especially in the field of modern information systems, new areas of application for robots and flexible automation in material handling must be developed to their fullest potential.

1.1 Background Information

According to Engelberger [5], one common method of classifying industrial robots is to examine the type of control system implemented to guide the robot through the desired operation. Limited sequence robots employ a system of mechanical stops or limit switches to control the movement of arm and gripper. They are the least sophisticated species of the robot family. Point to point robots are able to move to various positions between the limits of motion along each axis. Control is associated with the positioning of the robot at the completion of each motion. The path taken between each motion is arbitrary. The continuous path

control system is needed for applications in which it is necessary not only to control the start and finish points of a motion path, but also the path traced by the robot hand as it travels between these two extremes. Both point to point robots and continuous path control systems utilize servo control in obtaining the desired positioning.

The sequence of motion associated with a robot application must be programmed by the user of the system. As the application changes, the new or modified task requires reprogramming. A simple change in the location of a part feeder or the orientation of a holding fixture requires program modification. Current programming techniques often require the use of the robot in the actual production environment. "Teach pendant" programming allows the operator to drive the robot through the desired sequence of motions while identifying the end point of each path. Considerable production time can be lost during this programming process.

Palletizing refers to the process of stacking boxes, packages or finished parts on a platform or pallet. It is an important ingredient in an automated factory [16] because:

1. Space is used as efficiently as possible.
2. Parts, ordered in a pattern, facilitate pickup in the next manufacturing stage. This eliminates the need for tactual devices or computer vision.

While automatic palletizers are available for high volume long run

operations, robots offer an alternative for lower volume production.

According to Engelberger [3] and Abair [1], the most favorable conditions for using an industrial robot when designing palletizing patterns are given when the patterns change frequently and the process does not exceed a speed of 5 to 10 parts per minute. The development of a technique to improve the process of programming a palletizing operation would greatly increase applicability of robotics to this industrial task.

Some robot vendors offer special software options for palletizing operations. This is usually general in nature and results in a rectangular pattern of evenly spaced items.

An optimal pattern will only be reached in specific pallet and box configurations. In addition to time delays in manual software setup, hardware configurations in integrated palletizing systems require further improvement. The need for an interchangeability of end effectors is strongly related to automated systems so that idle time caused by manual gripper changes may be avoided.

1.2 Issues in Present Study

The purpose of the study was to demonstrate a method of tying together material handling, flexible automation, and a combination of on-line and off-line programming. This involved the

development of a "software package" to create an "optimal" pallet pattern and the corresponding robot control path. Additionally quick change mechanism and storage facilities for grippers were investigated, and owing to the necessity of special requirements, new designs were made and tested.

Frequently changing palletizing applications were selected to be the research framework, because they provide an ideal area to be subject to automation. The conducted case study proves that robot application can be optimized by avoiding time consuming off-line programming procedures and introducing automatic gripper change systems. Since some quick change mechanisms have already been introduced to the industrial market, the major issue in this research is to simplify the locking and unlocking mechanism and to make quick change systems generally applicable. One weakness of the commercially available systems is their restriction to be implemented only in certain predefined environments: some equipment is only adaptable to light assembly robots (Intelledex Inc.), others are only adaptable to medium sized or heavy duty robots (EOA Systems Inc.).

It is the scope of this research to close the gap between these two extremes to allow a quick change system to be used for small to medium sized robots. Research to avoid long programming efforts by employing a general software to create the robot control program, is lacking in literature. Robots are still programmed for

every changing situation. The present study emphasizes the development of a general palletizing software system. User input data is used to generate appropriate control commands thus relieving the operator of any programming task. Required input data is to be clearly defined and reduced to a minimum, so that even untrained personnel can handle the appropriate software.

1.3 System Environment and Setup

In order to demonstrate the feasibility of the integration of an off-line pattern generation process with a standard industrial robot, a workcell was created. The system consists of commercially available equipment, specially machined parts and system modeling components. Although limited in size, the setup was representative of an industrial palletizing operation. The system components included:

1. IBM 7545 robot with Intel 8080 controller.
2. IBM PC with 256 Kbytes Memory and two disk drives.
3. Fischer Technik conveyor.
4. Vacuum palletizing gripper with built-in sensor capabilities.
5. Quick change gripper adapter.
6. Carousel gripper storage.
7. Wooden blocks serving as substitutes for boxes.

The IBM 7545 Manufacturing System was selected for this research because of its relatively low cost, its (for a small robot) high

payload capacity, the high repeatability (+/- 0.002 inch), and its communication capabilities. It is programmed with an IBM Personal Computer (PC), using Version 4 of the AML/E robotics language. Some of the AML/E features are listed below:

1. Editor create and edit programs quickly.
2. Teachmode with graphic display of workspace and digital output control.
3. English-like commands, including commands for straight-line moves, palletizing support, and communication features.
4. Programmable speed.

Chapter II

LITERATURE REVIEW

The following literature review is subdivided into three major areas:

1. General robot palletizing/depalletizing applications.
2. Pallet pattern evaluation.
3. Interchangeable grippers and adapters.

2.1 General Robot Palletizing/Depalletizing Applications

The article, "Palletizing and Unitizing: How Robots Stack Up" [2], gives a general overview of palletizing techniques and the problems accompanied with this task. According to the authors, robots will never displace high speed palletizers, because the robot is still a low speed handling device. Robots, however, do have an appropriate place in industrial palletizing. Robots are not only able to position parts of any size, shape or weight precisely, they can also insert dunnage. Because of their flexibility, robots can stack cases of different products from a single infeeding conveyor onto several palletizing stations. In addition to these advantages, the palletizing robot is well suited to working with other automated equipment, as long as they are synchronized through bar codes or other means of identification. To enable the end effector to pick up multiple cases, a vacuum gripper is often the only choice.

The problem with this kind of grippers is that their tasks are limited to case weights of about 50 lbs. or less. If a heavy load has to be handled, a combination mechanical and vacuum gripper is often a good solution to this problem.

A comparison of high case palletizers with palletizing robots reveals that the hardware automation is faster, but it is not able to handle a wide variety of patterns and requires a great deal more floor space than a robot. The programmability and the gripper design allow the software automation to handle many different patterns. Additionally automatic palletizers are limited to handling boxes or cartons, while the industrial robot can manipulate a product directly.

Because of this wide range of variety, the development of efficient software remains a problem, since it is still impossible to purchase appropriate software directly from the retailer. The authors are of the opinion that the unique nature of most unitizing and palletizing applications is responsible for the need for special customized grippers and software.

Bengt Seger's [14] case study takes a complex palletizing application into consideration. The robot is applied to a bottling process. One type of box weighs 8 kg and arrives at the pickup station at a rate of 10 per minute, which amounts to 38,400 kg during an 8 hour shift.

A special gripper was designed for the 40 different sizes of cartons. The gripper is described as having two fingers. The upper finger serving as a holding plate and the lower one serving as a carrier. The lower finger can slide backwards on linear bearings, allowing the package to be placed on the pallet correctly. All 40 box sizes require separate programs, written and stored on magnetic tape. The author describes the programming operation as a time consuming task of 0.5 to 2.0 hours per program.

In Abair's [1] view, palletizing is an ideal area for automation, because all applications have at least one of the following characteristics in common:

1. Repetitive routine.
2. Multi-shift operation.
3. High volume output.
4. Strenuous labor-intensive method.
5. Tedious operations.

If short run products of various sizes with different pallet patterns are produced individually or simultaneously, robots are said to be cost efficient solutions. A typical robot cycle in a palletizing application is approximately 10 to 15 seconds from pickup to pickup. In order to optimize the path of the cycle, the entering parts have to be oriented beforehand. A suitable alternative for reducing overall cycle time is to provide a secondary palletizing location. Once the first load is completed, the robot can move to

the alternate location, and the operation can be resumed. The author found mechanical grippers to be the most useful although clearance requirements may prove a mechanical device to be unusable. However, the effect of inertia and accelerating forces have to be evaluated to ensure a secure transport when using magnetic or vacuum grippers.

Norbert N. Staufer [16] expresses the need for an ordered environment as an important prerequisite in the automated factory. Parts and material should be oriented accurately to make succeeding operations faster and easier. Palletizing and depalletizing operations accomplish these demands as an alternative to vision systems or other sensing techniques. According to Staufer, software changes, required in palletizing applications, are time consuming and have to be reduced to a routine exercise, which is limited essentially to indicating the orientation of the load, number of part locations per layer, and number of layers.

E. Grab [6] points out that the demand for further flexibility, reliability, and optimally of the storage capacity in the buffer area necessitates the increased use of automation systems between production and storage areas. A situation analysis of different representative production and logistic areas resulted in the realization that industrial robots are especially qualified in situations where the process time is defined by the machine production rate and limited by human work force capabilities. These

characteristics are common in palletizing, depalletizing , loading, unloading, and collecting applications. Traditional single purpose units are said to be well suited for batch production but include significant disadvantages: the unit is usually constructed for one specific product and the transferring to new product modifications is limited. The proposed "Unimation" robot palletizing center (RPC) includes the following advantages over the conventional system:

1. Universal use in spite of different, permanent changing products and variable quantities.
2. Off-line programming of different palletizing arrangements.
3. Easy alteration of changing production software.

The RPC system is guided by a supervisory controller. This computer controls all peripheral equipment for the loading process in which shipper containers are filled and then received by the UNIMATE robot. The pneumatic, parallel gripper is sensor equipped.

Ray Hinson [8] describes a palletizing application which is planned to be subject to automation. Currently the operation is performed manually. The same palletizing pattern is used until three stack levels have been placed on the pallet. In the succeeding step, the operator places a separator sheet over the stacked layer. The subsequent layer is palletized which is rotated 180 degree to provide stability to the pallet load. A tie sheet is placed over the second layer before the third and final level is palletized and rotated 180

degrees from the second layer. Based on individual stack weights of approximately 45 lbs, operators handle 28 tons of goods per shift.

Consideration must be given to all of the sensory capabilities employed and the coordination necessary to perform the task by means of robot automation. Removing as many variables as possible while minimizing the need for decision making can be accomplished by the creation of an orderly environment. Positioning of the pallet can no longer be an approximation. Also, further restrictions must be placed on the positioning of product stacks at the end of the conveyor. Additionally, if the requirement for dunnage sheet placement is to be fulfilled by the robot, the locating and positioning of the dunnage sheet supply is important. The presence of both pallet and product can be sensed by using contact switches which serve as substitutes for maintaining visual contact.

All sensory input is fed through a programmable controller to coordinate the system components and provide signals to initiate robot activities. The weight and design of the tooling will affect the performance of the robot in various ways. It can have a negative impact on robot's performance by being too large or too heavy, which will result in slower speed, or it can reduce the payload capability of the robot by introducing moments and loads which are out of its range of capacity.

An interesting approach of robot communication with external

devices in palletizing applications is described by G.S. Vasilash [19]. He is of the opinion that repetition jobs should be handled by machines instead of human beings to improve efficiency and work life quality. The particular application is described as follows: palletizing is performed 24 hours a day, seven days a week. A typical pallet load is 25 layers, each layer having 31 tubes. A counter is used to keep track of the number of layers placed on the pallet. Once the pallet is stacked to capacity, the conveyor is energized by a controller output signal to replace the full pallet with an empty one. The new pallet operates a limit switch that stops the conveyor and signals the robot to proceed.

The parallel tubes are automatically moved closer together into a queue at the end of the conveyor. When the queue consists of 31 tubes, the head tube tips a limit switch to signal the robot that it can pickup a load. The switch's second function is to operate a gate to halt the 32nd tube till the pickup location is cleared again. Before employing new robots to this palletizing task, extensive economic evaluations were conducted to compare robots to alternative automation equipment. It was established that the gravity operated conveyors offered higher economic justification, but were not able to handle an anticipated production-rate increase.

2.2 Pallet Pattern Evaluation

During the palletizing process, cartons or boxes are arranged in a pattern on a platform. Two properties of the pattern are important. The arrangement must attempt to make maximum use of space available. This will permit maximum utilization of the space when the product is shipped. Secondly the arrangement of the items must provide stability to the load as layer is stacked upon layer. This can be accomplished by changing patterns between layers.

Alexis Kulick [11] describes a computer simulation to develop pallet patterns. Since manufacturing is subject to frequent changes, the cost and possible inaccuracy of creating these patterns should be reduced significantly by means of computers. Each new shipper design may result in a new pallet pattern.

This paper deals only with the interlocking pattern, i.e. four of the five basic patterns have not been considered. Kulick also mentions that this simulation heuristic may not offer optimal pallet utilization. The interlocking character is achieved by turning each layer 180 degrees from the layer below, using the same pattern.

Harold J. Steudel [17], describes a heuristic to determine a loading pattern which tends to minimize the amount of unused pallet deck board area. To solve these two dimensional problems, dynamic programming is first used to determine four optimum sets of length

and/or width placements of the small rectangles (shippers) along the inside edges of the pallet. In the second phase, the optimum arrangement of rectangles along the perimeter is projected inward to fill in the center portion of the large rectangle so as to minimize the amount of unused area.

To establish the necessary geometric relationship, a pattern layout is designed to set up a maximum of four individual rectangular blocks of shippers. During the second phase of the model, two potential problems must be considered. For one, a condition of overlapping or mutual interference among the blocks could occur. The second problem is that the inward projections could result in a layout pattern with a central hole larger than a box. Certain procedures are established to solve interference and central hole problems.

By comparing these results with the results recommended by the U.S. Navy Supply Research and Development Facility, Steudel found that his algorithm exceeds the U.S. Navy standard by an average improvement of 10.4 percent in deck board utilization in 64 of 182 cases. The computer code for the algorithm is regarded as quite efficient and requires a total memory capacity of 14 K words and approximately 1.25 CPU seconds (Xerox Sigma 9) for any of the tested problems.

2.3 Quick Change Grippers/Interfaces

The authors of the article "Intelligent Interchangeable Robotic End of Arm Tooling [3]" point out that the role of flexible automation in industrial applications, including assembly and part handling, will expand rapidly with the commercial availability of computer-controlled interchangeable robotic end of arm tooling systems. A quick change adapter, mounted to the robot arm and to the end effector, provides the capability of performing multiple tasks in a single work station with an economic justification. The robot manufacturers are considered to be responsible for the existing gap in arm and end effector technology, because they have rushed to expand the robot technology but have overlooked the end effector research and development programs. The authors contend that this mistake is one reason for the slow growth of flexible automation in the U.S. Robot applications are usually limited to the implementation of tools which can perform only one task. The ability of executing multiple tasks within a single work station will add more product value and thereby emphasize cost justification. The described quick change adapter still has the disadvantage of being limited to a special range of application.

The article "Quick Change System for Robots" [20] asserts that in addition to the quick change adapter, a holster system for storing the end effectors is needed. It is necessary to equip the adapter with electrical and air connections, and it might even be necessary

to have access to hydraulic connections. The physical dimensions of the adapter described are quite large and limit its use to heavy duty jobs. The holster design must position the end effector with sufficient accuracy so that the robot can successfully change end effectors.

It is stated that the locking/unlocking mechanism must meet demanding requirements. It must be robust, lock and unlock with exceptional reliability. Ideally it has to be small and light weight and operate with shop air. Principles of kinetic energy are employed to enhance the capabilities of a small air vane actuator so as to ensure reliable unlocking and firm locking procedures. This technology requires a quite complex mechanism that must be purchased from specialized vendors.

Allen J. Wright [21] maintains that the key area of human versatility, or the ability to use several tools at a work station can be related to programmable automation by introducing interchangeable grippers. The following design objectives were considered necessary for the successful implementation of an end effector exchange mechanism:

1. Light weight.
2. Axial accuracy.
3. Longitudinal accuracy.
4. Rotational accuracy.
5. Coupling stiffness.

6. Torque capacity.
7. Connection of pneumatic and electric lines.
8. Full rotation capability of pneumatic and electric lines.
9. Easily adaptable to a variety of configurations.

Ellen J. Kehoe [10] illustrates that recent advances in end of arm tooling technology have broadened the choices available. Developments have been significant in the areas of interchangeable fingers and hands, sensory feedback capabilities, multi-fingered configurations, and the availability of standard models. As robots are called upon to perform more and more sophisticated, human-like tasks, expertise in designing and selecting robotic end of arm tooling is maturing accordingly. The combination of computer-sophistication and quick change tooling is also considered to offer increased flexibility adoption. The Quick Change adapter model from EOA Systems Inc. (Dallas, Texas) represents one example of interchangeable gripper technology. Configured to specific parts, this system can consolidate the palletizing of a low-volume product line into a single cell. Routing tools can be used in a single workcell while the component remains stationary. This precludes the need for additional robots.

2.4 Robot Languages and Palletizing

To make the palletizing software package as generally applicable as possible, different robot programming languages were investigated as to their implementation of the palletizing function. Robot programming languages can, according to Snyder [15], be subdivided into four major groups:

1. Task oriented: AUTO PASS.
2. Structured programming level: AL, MCL, MAPLE, PAL HELP, AML, KAREL.
3. Motion level: VAL, EMILY, RCL, SIGNAL, RPL, ANORAD.
4. Point-to-Point level: FUNKY, T3.

It is possible, though inconvenient, to implement a point-to-point level language in the manner done in this research, since programmed robot control is usually achieved by saving a series of points either by using a teach pendant or by moving the robot manually. Even though these languages are capable of interacting with external devices, FUNKY or T3 were hardly applicable to frequently changing palletizing tasks. One of their major disadvantages is that the programs generated are extremely long.

The motion-level languages exhibit the following characteristics:

1. Simple branching provided.
2. Subroutine can be used.

3. Parameters can be passed.
4. Sensing capabilities are relatively powerful.
5. The capability of representing and manipulating frame descriptions is provided.

Most of the motion level languages are based on interpreters or assemblers, and motion can be specified either in joint coordinates directly or in Cartesian coordinates. VAL, for example, applies shift commands to specify different locations. The command SHIFT PALLET does not cause any motion of the physical pallet; rather, it redefines a coordinate frame named PALLET. The next time the robot moves to the PALLET position, it will be a new position. The APPRO command is not only capable of specifying the desired position and orientation, it also specifies joint interpolated control.

The VAL structure is relatively similar to the BASIC structure and would be an excellent alternative to AML/E. A typical VAL palletizing program is listed below [18]:

```
1.        SETI  PX = 1
2.        SETI  PY = 1
3.  10    GOSUB  100
4.        IF PX = 3 THEN 20
5.        SHIFT PALLET BY 100.0,0,0
6.        GO TO 10
7.  20    IF PY = 3 THEN 40
```

```
8.        SETI PX = 1
9.        SETI PY = PY + 1
10.        SHIFT PALLET BY - 900.0, 100.0,0
11.        GOTO 10
12. 100    APPRO CON, 50
13.        WAIT CONROY
14.        MOVES CON
15.        GRASP 25
16.        DEPART 50
17.        MOVE PALLET: APP
18.        MOVES PALLET
19.        OPENI
20.        DEPART 50
21.        SIGNAL GOCON
22.        SETI PX = PX + 1
23.        RETURN
24. 40     STOP
```

The pallet consists of three rows and three columns of squared boxes. Lines one and two initialize integer variables which keep track of the number of parts already loaded in both the X and Y axes. The GOSUB located in line three calls a subroutine which will unload one part from the conveyor and place it on the pallet. The SHIFT command in line five implements a translation of x = 100.0 mm, y = 0, and z = 0. The APPRO function causes motion to a point 50 mm distant from the Z axis of the designated frame

(CON). The command on line 13 allows the robot to wait for a signal from a limit switch, indicating that the conveyor is ready. The manipulator then moves to the grasp position and closes the gripper. If the hand closes to less than 25 mm, an error is assumed, and the program is temporarily discontinued. The DEPART command specifies Cartesian motion. In line 21, the conveyor is started by an output signal.

Snyder points out that the structured programming level incorporates structured control into the robot language, and that the use of coordinate transformations and frames is provided extensively. Additionally, the typical language at this level has definable subroutines with parameter passing. With MCL and AL it is possible to fix frames together so that transforms applied to one part are automatically applied to another. All languages at this level could probably have been implemented successfully, but AML/E is the only one with a palletizing function, so that its use is preferable and is the language of the robot present in the laboratory.

Snyder [18] points out that task oriented robot programming languages are still a unachieved concept. They require a sophisticated world modeling system to keep track of objects. Palletizing commands would be passed in resembling instructions that might be given to a human assembly worker.

2.5 Concluding Remarks on the Review of Literature

While the industrial robot will not replace automatic palletizers in the foreseeable future, there are many areas of applications in palletizing for todays robots. The programmability and flexibility of the robot are ideally suited for operations that have frequent changes or slower cycle times. Additionally the robot is capable of direct part handling and is suitable for inprocess palletizing while automated systems are limited to finished products that have already been packaged.

All of the authors cited in section 2.1 agree that software development for palletizing applications still has major drawbacks. Most vendors do offer some solution packages, but these must still be customized for each different application. The articles reviewed which discuss pallet patterns give some examples of algorithms that can be applied to this situation, but the latter are not integrated into robot software.

The literature reviewed in the third section of Chapter II emphasizes the need for research in this special field of flexible automation. All articles reviewed describe already in existence equipment but show clearly that an all-purpose system is still not commercially available. Examples of general palletizing algorithms, used in robot control, are completely lacking in literature on this subject.

Chapter III

SOFTWARE SYSTEM DESIGN

The software system developed in this research consists of three parts. A pallet pattern generation program utilized user input data to generate a desired pattern using the algorithm as presented by Kulick [11], or using a newly developed combined heuristic. The established pattern was then used as input for generating the necessary robot control commands in the AML/E robot programming language. An IBM PC batch file then controlled compilation and downloading of the file to the robot control system. The software was run on an standard IBM PC with 256 Kbytes of memory, dual floppy disk drives and a color adapter and monitor. The software system was developed in a modular fashion to permit a variety of algorithms to be included.

3.1 Pallet Pattern Generation

AML/E provides the user with a palletizing function to be used easily in applications not subject to frequent changes. Its major weaknesses are a lack of flexibility and a low average pallet utilization caused by the fixed nature of the pattern. IBM dictates the use of an rectangular pattern, independent of pallet and box size ratio. Changes in pattern geometry or stacking sequence can only be made through increasing the complexity of the program structure. To use the

AML/E palletizing support, the programmer must define the lower left corner point of the pallet, the lower right corner point, the upper right corner point, the number of parts per row, and the total number of parts per layer. If the number of parts per row and the total number of parts per layer are identical, the AML/E palletizing support cannot be used, because the controller interprets this configuration as a data error, i.e. a one-row layer cannot be stacked. The palletizing function may be used in applications with customized pallet forms and dimensions, but not as a general purpose solution for pallet pattern generation.

The interlocking pattern [11] consists of layers of shippers, placed in two directional patterns. To create the interlock, each layer is stacked 180 degrees from the layer below using the same pattern. The interlock receives its support from the overlap of shippers between two layers. The height dimension of the boxes will always remain perpendicular to the pallet.

The implemented heuristic [11] divides the pallet into two sections. The shippers in one section are perpendicular to the shippers in the other. There are two possible ways of "cutting" the pallet into two rectangular divisions: parallel to the long side (length), or parallel to the short side (width) of the pallet. This is illustrated in Figure 3.1.

Both of the cases cited above are to be considered in the heuristic. The final size of the sections (for a given pallet) depends on the shipper length and width. A number of different configurations are checked, and the pattern with the highest pallet utilization is selected as a basis for further evaluations. The result is expressed in the number of boxes perpendicular to the long side (length) and parallel to the short side (width) for the first pallet section and parallel to the length and perpendicular to the width of the second pallet section as shown below:

Example: first section:

x_1 = number of boxes parallel to width

x_2 = number of boxes perpendicular to length

=> total number of boxes in section I: $x_1 * x_2$

Example: second section:

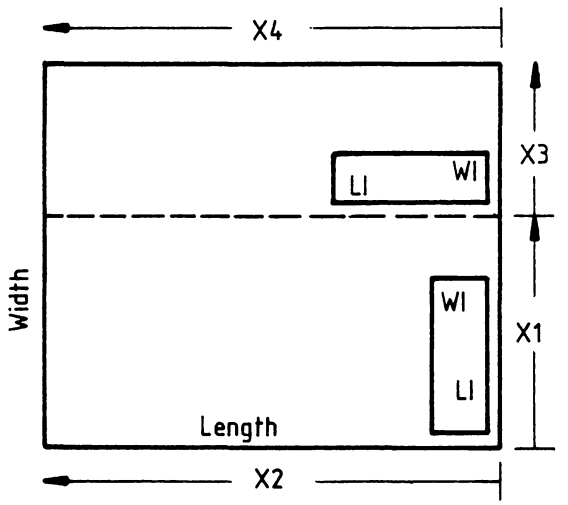
x_3 = number of boxes perpendicular to width

x_4 = number of boxes parallel to length

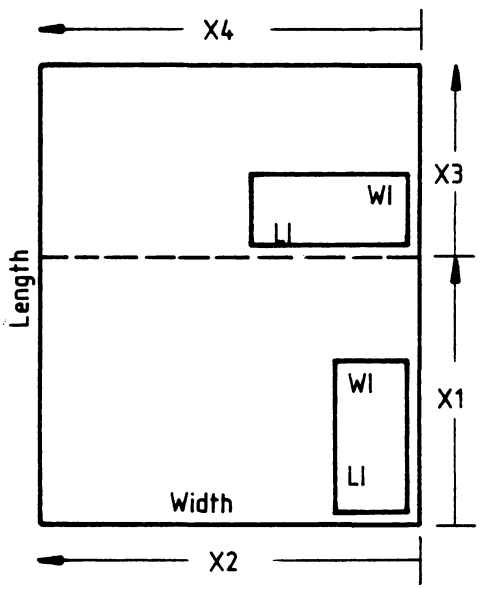
=> total number of boxes in section II: $x_3 * x_4$

(See Figure 3.1)

Pattern 1



Pattern 2

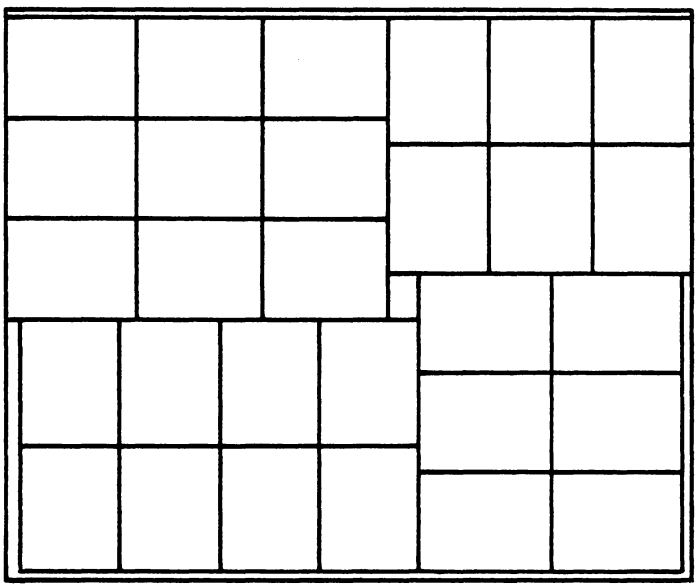


	Name	Date		
Work			Figure 3.1 Pallet Sections	
Check				

3.2 An Alternative Algorithm

An alternative to using the interlock algorithm is the "Two Dimensional Cutting Stock" algorithm [17]. The pallet loading problem [17] can be viewed as a special case of the two dimensional cutting stock problem, where all the objects to be arranged are of identical dimensions. The objective of this problem is to determine a layout for which the ratio of unused space to the total area of the pallet is kept to a minimum. To solve this problem a two phase algorithm has been developed [17]. Dynamic programming is first applied to determine four optimum sets of length and/or width placements of the boxes along the edges of the pallet, as shown in Figure 3.2. The objective of the algorithm's second phase is to project an optimal arrangement of the shippers inward to fill the center portion of the pallet.

To establish the necessary geometric relationships, a pattern layout is defined as consisting of a set of a maximum of four blocks of shippers. Overlapping or mutual interference among blocks could occur, or the inward projection could result in a layout pattern which has a central hole larger than a box. Both problems must be taken into consideration and solved to fulfill the requirements.



	Name	Date		
Work			Figure 3.2 Pallet Pattern	
Check				

The pallet utilization reached with this algorithm was compared to the pallet pattern recommended by the U.S. Navy Supply Research and Development Facility. An average improvement of 10.4 % in deck board utilization in 64 out of 182 cases was established [17]

The second implemented heuristic, developed in this research, was a combination of "Interlock " [11] and "Two Dimensional Cutting Stock" [17] algorithm. Both were used as a first starting base to create a new heuristic. The program divides the pallet into 4 sections, like the "Two Dimensional Cutting Stock" algorithm, but establishes a common intersection for all four regions. This guideline was implemented because it guarantees a high probability for an interlock pattern in a wide range of cases. The two diagonal opposite sections have the same patterns but are perpendicular to each other.

The first section is used as a starting point and every possible combination of boxes in the four regions on the pallet is enumerated accordingly. The box configuration with the highest pallet utilization is used to establish the final pattern. The idea of combining structures of "Interlock" and "Two Dimensional Cutting Stock" algorithm was based on the acceptance of providing the interlock advantages by reaching a very high pallet utilization. This goal was not reached fully, although the heuristic was proved to be a very useful alternative. The implementation in the overall software package was established easily, since the system was conducted in a modular fashion. Except for the actual heuristic section, only minor

changes had to be made. The AML/E palletizing function was used for all four pallet regions individually, and the result is expressed in the number of rows and columns per region and the total number of boxes per layer and pallet.

3.3 Comparison of the Algorithms

To evaluate the performance of both heuristics, interlock and combination heuristic, layout patterns for a 40 inch by 48 inch pallet were generated in 0.50 increments for items ranging in size from 5.00 inches to 10.5 inches width and from 7 inches to 15 inches in length. The resulting patterns for 167 cases were then compared in terms of the number of items per layer to the pallet patterns recommended by the U.S. Navy Supply Research and Development Facility as reported by Haynes [7]. The interlock heuristic provided an improvement of 7.34% compared to the Navy standard and the combined heuristic "only" reached the Navy standard (99.88% of Navy standard).

A closer look at the results discovered the real strength and weaknesses of the combined heuristic: the pallet utilization decreases with increasing box sizes, especially if boxes with 5 to 7 inches width and 12 to 15 inches length have to be stacked, a utilization improvement of 3.78% (compared to the U.S. Navy standard) can be achieved, so that this heuristic can be strongly recommended in applications with these particular box sizes.

3.4 Robot Motion Command Generation

There are basically two ways to implement the outcome of the used heuristics into the software frame to generate the robot control path for an "optimal" pattern. For one the geometric location of every single box for every layer has to be calculated and implemented into AML/E. Using this method assumes that every shipper transport requires the generation of at least six AML/E statements:

1. Move the manipulator above the conveyor.
2. GRASP the box.
3. Move the manipulator in positive Z direction.
4. Move the manipulator above the pallet.
5. RELEASE the box.
6. Move the manipulator in positive Z direction.

The maximum AML/E file size restriction allows no more than 800 lines for personal computers with 256 KBytes memory. When one considers a pallet load of 10 layers and 40 boxes per layer, the robot control path will require 2400 statements. Since multiple statements per line are allowed, the number of lines will be reduced to approximately 600, i.e. up to 75% of the total editor capacity is utilized solely for the stacking process.

The second alternative is the use of the AML/E palletizing function. As the interlock heuristic, for example, divides the pallet into two sections with rectangular patterns that are perpendicular to each

other, the AML/E palletizing function can be employed for each of these sections separately. Taking advantage of the language support, the generated robot control program is significantly shorter, and the compiler time is reduced by approximately 1/3.

In some cases the box and pallet size ratio dictates a pattern configuration in which the first pallet section consists of two to four rows, and the second section consists of only one row, perpendicular to the other rows. In such a situation it is necessary to create a dummy row which will not be used. This is because the AML/E palletizing function does not allow single row pallets. An analysis of both above mentioned methods, indicated that the use of the AML/E palletizing function guarantees the most efficient solution in terms of compiler time and memory use.

One alternative approach to the conventional program generation, compiling and loading process is the use of host computer communication. Host communication operations [9] involve the exchange of record transactions between the robot controller and a host computer. These transactions are described by a protocol. The protocol includes both a statement of transaction format and an acceptable sequence of transaction records.

AML/E Version 4 uses two types of communication, host-initiated and controller-initiated. Each is able to transfer data from the host to

the controller (a data drive direction) or from the controller to the host (a report direction). The data drive direction allows the host to affect the application that is being executed by the controller. The communications interface supplied with AML/E Version 4 is a low level interface used in conjunction with machine language, i.e. records are transmitted and received in ASCII code.

In this study the controller initiated communication is of major interest, because it allows the user to change the value of variables in controller storage without interfering in the application program. It allows the user to maintain many parameters of point data in the host computer and to load the points into an application program before execution is initiated.

Utilizing host computer communication a palletizing program would permit implementation of the logic to be shared between the host computer and the robot controller. Actions which do not change, part pickup, gripper exchange, etc. would be implemented on the robot controller. The host software would keep track of the pattern point sequence and geometric data. Commands and pallet points could then be passed to the controller when applicable. While this approach has significant merit, it does require the dedication of a host computer during the operation. Additionally, assembly language interface routines are necessary to drive the communications process. For these two reasons, this approach was not taken in this research.

3.5 Description of Software System

The pallet generation algorithm and the program to transform the geometric pattern into AML/E robot motion commands were combined into a single FORTRAN 77 program and implemented with the MICROSOFT FORTRAN compiler version 3.2. This program generated the source control program for the robot by writing into an external disk file. The autoexecution function for the IBM PC was then used to cause the AML/E compiler to read the file, create code for the robot controller and then down load the file for execution. To start program operations, the personal computer must be connected to the controller; the controller must be ON LINE, and the manipulator must be powered on.

Boot loading the user disk in drive A causes the "AUTOEXEC.BAT" file to start the FORTRAN program. In the interactive phase, the user selects the unit of measurement (inches or millimeters), and is requested to input data on shipper dimensions and weight, and maximum pallet height, as well as whether the system is working with or without dunnage. Table 3.1 illustrates the initial dialog. The program assures a pallet size of 9.6 inches by 8.0 inches however this could easily be modified. According to the input data, the heuristic calculates an optimal interlock pattern and informs the user about pallet utilization, number of boxes per layer, and total number of boxes to be stacked.

The AML/E control program is then generated in the second phase of the FORTRAN program and written into the "NEW.AML" file on the user's disk. The implementation of the AML/E statements was reached by using Boolean algebraic decision functions and FORMAT statements. Depending on the input data, only certain parts of the program become active. If the user decides to work without dunnage, an IF Then statement is used to skip the program part in which the AML/E dunnage stacking code is generated. This principles are extensively used throughout the entire software, so that the development of unused AML/E subroutines is avoided.

Table 3.1 User options

First screen:

THIS PROGRAM CALCULATES AN INTERLOCK PATTERN

TYPE 1 IF YOU WISH THE INPUT IN INCHES

TYPE 0 IF YOU WISH THE INPUT IN MM

ENTER OPTION ==> Next screen:

PLEASE GIVE WIDTH OF SHIPPER

ENTER OPTION ==>

Next screen:

PLEASE GIVE LENGTH OF SHIPPER

ENTER OPTION ==>

Next screen:

PLEASE GIVE HEIGHT OF SHIPPER

ENTER OPTION ==>

Next screen:

PLEASE GIVE MAX. PALLET HEIGHT

ENTER OPTION ==>

Table 3.1 User options

Next screen:

TYPE 1 IF BOX WEIGHT IS IN THE RANGE OF

0 - 5 LBS

TYPE 0 IF BOX WEIGHT IS IN THE RANGE OF

5 - 10 LBS

ENTER OPTION ==>

Next screen:

TYPE 1 IF THE PALLET SHALL BE STACKED

WITH DUNNAGE, ELSE TYPE 0

ENTER OPTION ==>

Last screen (dunnage option):

PLEASE GIVE THICKNESS OF DUNNAGE

ENTER OPTION ==>

The "NEW.AML" file is opened and closed automatically and includes the complete robot control program. The "AUTOEXEC.BAT" file initiates the compiler on the AML/E system disk in drive B and indicates appropriate options. The robot controller is automatically loaded with the compiled ASCII file, and the user may begin the cycle by pressing the following sequence of buttons on the robot control panel:

1. Return Home.
2. Automatic.
3. Application I.
4. Start cycle

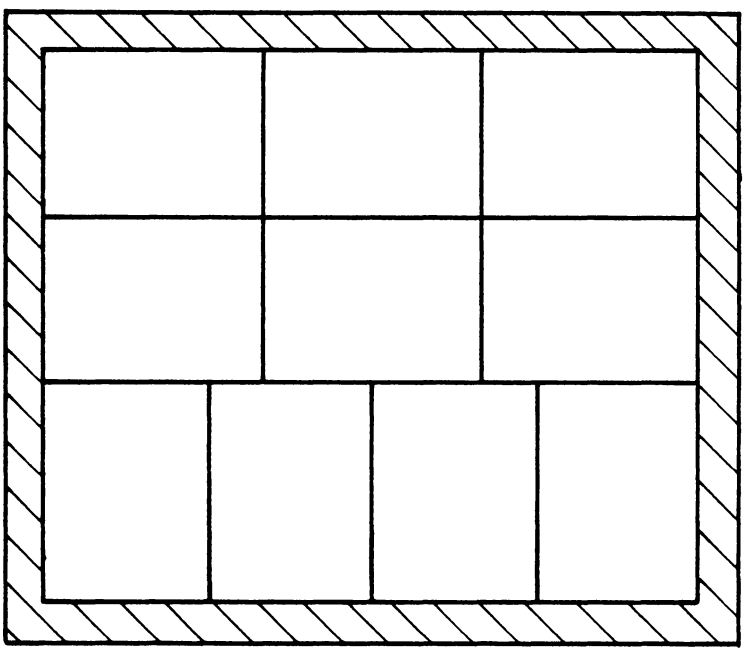
3.6 An Example Application

An example problem was implemented with both pallet pattern heuristics. It showed that the combined heuristic is most likely to generate an interlock pattern, when possible. The following input data was assumed:

Input system	: inches
Shipper width	: 2.40 inches
Shipper length	: 3.20 inches
Shipper height	: 0.75 inches
Max. pallet height	: 3.00 inches
Shipper weight	: 5 - 10 lb
Dunnage	: yes
Dunnage thickness	: 0.1 inches

According to the above listed input, the FORTRAN program generates an AML/E control path to guide the manipulator through the palletizing task. Both heuristics generate the same interlock pattern for this particular case and based on this information, the palletizing sequence is specified. The sequence of steps necessary to perform the palletizing function is then begun. The manipulator with the quick change adapter attached, moves above the gripper carousel. The robot controller then rotates the carousel to the home position and then to the heavy box gripper position. The manipulator moves down and the vacuum gripper is locked onto the robot arm. The robot slides the gripper out of its storage slot and moves in positive Z direction. The conveyor is turned on automatically, and the manipulator waits for a box to arrive at the pickup location. If no box arrives within 15 seconds, an attention light informs the operator of the problem. The operator then corrects the problem and presses the restart button for normal operating conditions.

As boxes arrive at the pickup point, a limit switch is pressed. This signals the robot that the box is ready for pickup and also turns off the conveyor drive motor. When the robot completes the cycle from the previous operation, it tests the status of the limit switch and begins a new operation cycle. The arm is positioned to pick up a box, the gripper is activated, the box is taken to the desired pallet position and the box is released. This cycle continues until the pattern is completed. In this example, each layer consists of 10 boxes, stacked according to the optimal interlock pattern as shown in Figure 3.3.



	Name	Date		
Work			Figure 3.3 Interlock Pattern	
Check				

After each layer is completed, the manipulator moves over to the carousel and the controller rotates the turn table to the home position and then to the heavy box gripper slot. The robot arm slides the gripper in its slot, unlocks the quick change adapter, and moves in positive Z direction to disengage the gripper. The controller rotates the carousel to the dunnage gripper below the robot end of arm.

The manipulator moves down, locks the quick change adapter, slides the dunnage gripper out of its slot, and moves over to the dunnage stack. After putting a pasteboard on the current layer, the manipulator parks the dunnage gripper, retrieves for the heavy box gripper and continues the palletizing sequence for the next layer. As soon as a pallet is stacked to capacity, an attention horn signals the operator to replace the full pallet with an empty pallet and press the restart cycle button to begin the process again. If the operator fails to replace the pallet within 30 seconds, the robot parks the palletizing gripper and moves back to the home position.

3.7 AML/E Subroutines and Descriptions

The most important AML/E subroutines are listed and explained below:

```
INTERCHANGE_BEGIN_HEAVY:SUBR;
   PMOVE (INTER); PAYLOAD (11); SET_HOME; ROTATE (25);
   ZONE(1);
```

```
   ZMOVE (MATE); WRITEO (ZYLINDERI,ON); LINEAR (1);
   DELAY (2);
   PMOVE (SEMI); PAYLOAD (0); ZMOVE (0); WRITEO (15,ON);
   LINEAR (0);
END;
```

The INTERCHANGE_BEGIN_HEAVY subroutine is used to guide the robot through the heavy-load-gripper pickup sequence. The end of arm moves to a point above the carousel, specified by the global variable INTER in the PMOVE statement. The PAYLOAD (11) statement declares that the next manipulator move will be executed in a very slow speed. After the speed has been specified, the SET_HOME subroutine is called to generate a number of pulses to rotate the carousel from an arbitrary position to the home position.

The next command locates the heavy weight gripper correctly by calling the ROTATE subroutine and passing the formal parameter 25 to this subroutine. The ZONE (1) statement assures a high degree of accuracy for the following moves. The manipulator moves down to mating depth, which is passed through by the global variable MATE. The DO port 1 (specified by the global variable ZYLINDER1) is closed, so that the locking cylinder is actuated. The cylinder rod then extends to lock the quick change adapters, and execution is halted for 2 seconds to assure that the cylinder rod has been fully protracted.

After the robot has slid the gripper out of its holster (PMOVE (SEMI)), the speed is maximized with the PAYLOAD(0) and LINEAR(0) commands, and the manipulator moves in the positive Z direction to avoid collisions with obstructions. The DO port 15 is then closed to start the conveyor.

```
SET_HOME:SUBR;
   LOOP: WRITEO (STEP,OFF); DELAY (0.1); WRITEO (STEP,ON);
   DELAY (0.1);
   TESTI (HOMEI,ON,DONE); BRANCH (LOOP);
   DONE: BREAKPOINT;
END;
```

The SET_HOME subroutine is used to create a string of pulses to rotate the carousel from an arbitrary position to the defined home position. Every WRITEO command is followed by a delay of 0.1 seconds to allow the manual relay to change its status (from closed to open, or from open to closed). The DI port 9 is tested after each completed pulse to see if the home position of the carousel has been reached. As soon as the limit switch is actuated by the stop, DI port 9 closes and execution is interrupted. The BREAKPOINT provides the user with the ability to interrupt execution before the next subroutine has been started.

```
ROTATE: SUBR(DEGREE);
   SETC (TURN,1);
   LOOP: WRITEO (STEP,OFF); DELAY (0.1); WRITEO (STEP,ON);
   DELAY (0.1);
   TESTC (TURN,DEGREE,DONE); INCR (TURN); BRANCH (LOOP);
   DONE: BREAK POINT;
END;
```

The ROTATE subroutine is employed to rotate the table to a certain angle, specified by the formal parameter DEGREE. The angle to be achieved, is specified by the number of pulses (number of completed cycles inside the loop) and depends on the gripper holster which must be turned into position. The internal counter is first set to one before beginning the pulse loop. The WRITEO, DELAY, WRITEO, DELAY sequence of commands creates an electrical pulse on the step output line, DO port 16. The internal counter is then compared to the input value, and the loop terminates or the counter is incremented and the loop repeated. The state of completion is checked by the TESTC (TURN, DEGREE, DONE) statement, in which the counter value TURN is compared to the formal parameter DEGREE. Again the BREAKPOINT statement is included to permit the user to interrupt program execution before continuing with the next subroutine.

```
DUNN_GRIPPER_ROTATE: SUBR (PLACE5);
   PMOVE (SEMI); LINEAR (1); SET_HOME; ROTATE (25);
   PMOVE (CAROUSEL); WRITEO (ZYLINDER1 OFF); DELAY (2);
```

```
   WRITEO (ZYLINDER2, ON); DELAY (4);
   WRITEO (ZYLINDER2,OFF); DELAY (5);
   ZMOVE(0); SET_HOME; ROTATE (50); DELAY (2); ZMOVE (MATE);
   WRITEO (ZYLINDER1,ON); DELAY (4); PMOVE (SEMI);
   LINEAR (0);
   PMOVE (DUNN_PICKUP); GRASP; DELAY (1);
   PMOVE (PALLET_CENTER); GUARDI (8,ON); ZMOVE (PLACE5);
   NOGUARD; RELEASE; DELAY (1); ZMOVE (0); PMOVE (SEMI);
   LINEAR (1); SET_HOME; ROTATE (50); PMOVE (CAROUSEL);
   WRITEO (ZYLINDER1,OFF); DELAY (2);
   WRITEO (ZYLINDER2,ON); DELAY (4);
   WRITEO (ZYLINDER2, OFF); DELAY (5); ZMOVE (0);
   SET_HOME; ROTATE (50); DELAY (2); ZMOVE (MATE);
   WRITEO (ZYLINDER1,ON); DELAY (2); PMOVE (SEMI);
   LINEAR (0);
END;
```

The DUNN_GRIPPER_ROTATE subroutine is applied to replace the palletizing gripper with the dunnage gripper and to place a pasteboard sheet on the current layer. The manipulator moves to an intermediate point (SEMI) in front of the carousel, waits for the correct holster to be located, and then slides the gripper into its holster in a linear fashion, so that the forces of friction may be kept to a minimum. The locking cylinder is activated by DO port 1, execution is halted for 4 seconds to assure a complete retraction process, and the 2nd cylinder is actuated and deactuated again by DO port 5 to unlock

the quick change adapters. The carousel revolves again, the dunnage gripper is picked up, the robot moves above the dunnage supply stack, the coordinates of which are passed through by the global variable DUNN_PICKUP. The move in minus Z direction to put the pasteboard on the pallet is guarded by the GUARDI (8,ON) statement. When the gripper's limit switch signals that the dunnage is touching the box surface, DI port 8 closes and the motion is interrupted. The NOGUARD statement ends the guarding phase. The palletizing gripper is picked up again, and the palletizing sequence is resumed.

```
WAIT_PART;SUBR;
   WAITI (PORT,ON,15,TROUBLE);
   BRANCH (DONE);
   TROUBLE: WRITEO (OPER_ATTNHORN,ON);
   WAITI (OPER_RETRY,OFF,0); WAITI (OPER_RETRY,ON,0);
   WAITI (OPER_RETRY,OFF,0); WRITEO (OPER_ATTNHORN,OFF);
   DONE: BREAKPOINT;
END;
```

The WAIT_PART subroutine was conducted to control the flow of material to insure that the robot does not attempt to pick up a nonexistant box. During this phase of the application, the WAITI statement is used to optimize throughput within the framework of preset time economy restrictions. If the port does not attain the primary specified value (here "1") within 15 seconds, the control branches automatically to a predefined sublabel. That is, if no box

arrives and presses the conveyor limit switch within 15 seconds, the control branches to the label TROUBLE. Should this occur, the operator attention horn is actuated by DO port 11. The controller waits an infinite period of time for the operator to press and release the retry toggle switch to signal the controller that the problem has been solved and normal performance can be resumed. The WRITEO statement is not only used to initiate the attention horn, but also to shut it off when normal conditions again prevail.

```
NEW_PALLET: SUBR;
   WRITEO (OPER_ATTNHORN,ON); WAITI (OPER_RETRY,OFF,5);
   WAITI (OPER_RETRY,ON,25,LOOP_PARK);
   WAITI (OPER_RETRY,OFF,10); WRITEO (OPER_ATTNHORN1, OFF);
   BRANCH (DONE);
   LOOP_PARK: ZMOVE (0); PMOVE (SEMI);
   WRITEO (15,OFF); WRITEO (OPER_ATTNHORN,OFF);
   SET_HOME; ROTATE (25); LINEAR(1); PMOVE (CAROUSEL);
   WRITEO (ZYLINDER1,OFF); DELAY (3);
   WRITEO (ZYLINDER2,ON); DELAY (3);
   WRITEO (ZYLINDER2,OFF); DELAY (5); LINEAR (1);
   ZMOVE (-150); LINEAR (0); ZMOVE (0);
   DONE: BREAKPOINT;
   WRITEO (OPER_ATTNHORN,OFF); PMOVE (PT(650,0,0,0));
END;
```

The NEW_PALLET subroutine is called by the last palletizing subroutine

to signal to the operator that the current pallet has been stacked to capacity. At the sound of another attention horn, the operator has 25 seconds to replace the full pallet by an empty one and press the restart toggle switch. If he or she fails to press the button within 25 seconds, the robot considers the shift to be over, parks the gripper, and moves back to the home position.

```
PICKUP;SUBR (PLACE1);
   SET: SET_PART (SAMPLE1,1);
   LOOP; WAIT_PART; PMOVE (PICKY); ZMOVE (PICKZ);
   GRASP; DELAY (1); ZMOVE (0); GETPART (SAMPLE1);
   GUARDI (8,1); ZMOVE (PLACE1); NOGUARD; RELEASE;
   DELAY (1); ZMOVE (0); TESTP (SAMPLE1,N1 REAL, DONE);
   NEXTPART (SAMPLE1);
   BRANCH (LOOP);
   DONE: BREAKPOINT;
END;
```

PICKUP is the first of 4 subroutines to establish the interlock pattern. All four routines are very similar and differ only in the number and orientation of parts to be stacked, and box coordinates on the pallet. Each pallet pattern is made up of 2 differently sized sections, consisting of perpendicular patterns. Although these sections are turned 180 degrees to create the interlock, the patterns themselves do not change. When the two patterns needed to define one

layer are rotated, the first pattern to be filled becomes the second and the second, becomes the first. Additionally, since the patterns are both rotated and translated in the space of the workcell, the points defining the corners of definition changes. Each of the sections requires a separate AML/E subroutine to establish the stacking sequence, i.e. 4 subroutines are necessary to define a pallet with any number of layers, greater than or equal to two. The appropriate Z value which changes for every layer to be stacked is passed through by the formal parameter PLACE1.

SAMPLE1 is a global pallet variable, used to identify the lower left corner, the lower right corner, the upper right corner, the number of parts per row and the total number of parts per pallet section. This information is required if the AML/E palletizing function is to be used. The SETPART statement defines the stacking sequence, i.e. in a palletizing task the first part is set equal to 1, in a depalletizing task the first part is set equal to the total number of parts, and the counter value is increased or decreased accordingly.

The first statement inside the loop calls the WAIT_PART subroutine to insure that the parts to be picked up are present. The robot moves to the conveyor and grasps a box in the command sequence PMOVE, GRASP, DELAY, AND ZMOVE. The GETPART command locates the end of arm above the correct spot according to the even row patterns. The GUARDI, ZMOVE, NOGUARD cause the robot to lower the arm in a guarded fashion. This involves the checking of the gripper limit switch during the

robot motion. If the box contacts another layer while being lowered, motion is stopped. Since box heights are not always consistant this may be necessary. The RELEASE and DELAY commands deactivate the gripper. After the box has been set down, the counter value is compared to the actual number of boxes with the TESTP statement. If both numbers are identical, the subroutine is completed. If SAMPLE1 is less than N1REAL, the loop is repeated.

Chapter IV

HARDWARE SYSTEM DESIGN

Implementation of a working demonstration of a flexible system for robot palletizing necessitated hardware, as well as, software consideration. Hardware design provisions were subject to restrictions created by the commercial availability of parts and by the machinability of parts in the IEOR machine shop which would meet industrial standards. Specifically addressed in the study was a special purpose vacuum gripper for box pickup, a quick change mechanism to allow gripper exchanges, and a carousel for holding different robot end effectors.

4.1 Palletizing Gripper Design

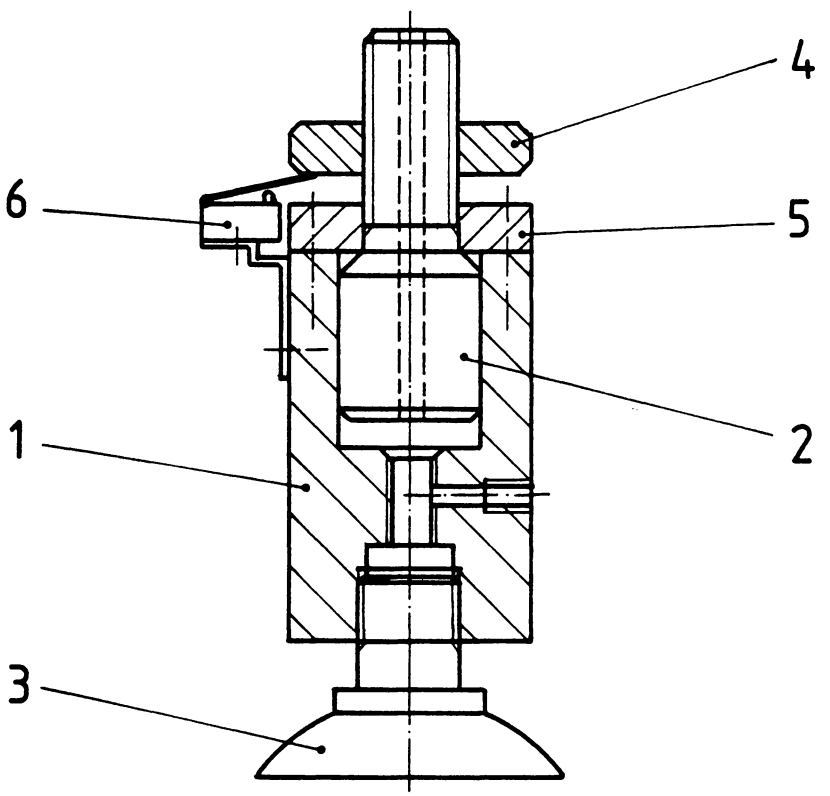
To keep the research costs as small as possible, a palletizing gripper was designed and machined in house, instead of buying appropriate equipment. The special purpose vacuum gripper was designed, not only to satisfy basic palletizing requirements, but also to presuppose a certain degree of intelligence to allow a feedback control. The following design objectives were considered necessary for the successful implementation of the palletizing end effector:

1. Light weight.
2. Axial accuracy.

3. Rotational accuracy.
4. Compensation of shipper height tolerance of up to 1/8 inch.
5. Suction capacity up to 10 lbs.

The gripper consists of 5 parts; its largest diameter is 2 inches, its maximum length 4 inches, and its weight approximately 0.5 lb. (see Figure 4.1).

The aluminum body (1) was machined to take the brass piston (2). The squared clearance form fit allows the piston (2) to slide up and down, while preventing it from revolving inside the body (1). The clearance fit was machined with close tolerances to fulfill the axial and rotational accuracy requirements. The rubber suction cup with threaded shaft (3) was screwed into the body (1) and connected to the vacuum pump. The aluminum nut (4) is used to adjust the piston's path of movement and as an actuator for the limit switch (6). The aluminum cover plate (5) keeps the piston from sliding out of the body. The material combination of aluminum and brass for body and piston assures a minimum of material wear and maintenance. The piston is mounted to the quick change adapter and provides the stiffness necessary for axial accuracy. A vacuum tube is connected to a sensor equipped vacuum valve to monitor suction intensity between gripper and box. Box contact sensing is provided by and a normally-open limit switch (6), so as to maximize system efficiency and to protect the component part from damage.



	Name	Date	Scale: 1:1	
Work			Figure 4.1 Pallelizing Gripper	
Check				

If the box tolerance exceeds 1/8 inch, the limit switch provides a signal to the controller to stop the manipulator movement in the -Z direction. This is uses in combination with the AML/E GUARDI statement. The GUARDI [9] command allows to use a DI (digital input) port to guard motion. Based on external input , the GUARDI statement interrupts any motion dealing with unexpected box sizes. As a movement occurs, the controller monitors the port value. If the DI point attains the specified value, motion is terminated. The manipulator does not stop program execution, but regards the particular move as completed.

Mechanical grippers can be regarded as alternatives to special palletizing grippers discussed above. The advantage of mechanical grippers is related to their greater flexibility in non palletizing applications and in their capability of handling heavy and hot parts. Mechanical gripper designs may be as simple as a single moving finger pushing the object against a stationary stop. More complex designs tend to imitate the complexity of the human hand. The problem associated with mechanical grippers is the difficulty when they are encountered in applications with restricted loading clearance between boxes to be stacked. If the part is of ferrous content, magnetic pickups are a considerable alternative to vacuum and mechanical grippers.

4.2 Quick Change Mechanism

The general purpose quick change mechanism was designed to give greater flexibility to the robot. The ability to change end effectors automatically is an important step in making robots better adaptable to applications subject to frequent changes. The quick change system puts the multiple tool capability at the disposal of a robot, and in some cases even allows a robot to be considered for an application that it otherwise would not be able to handle.

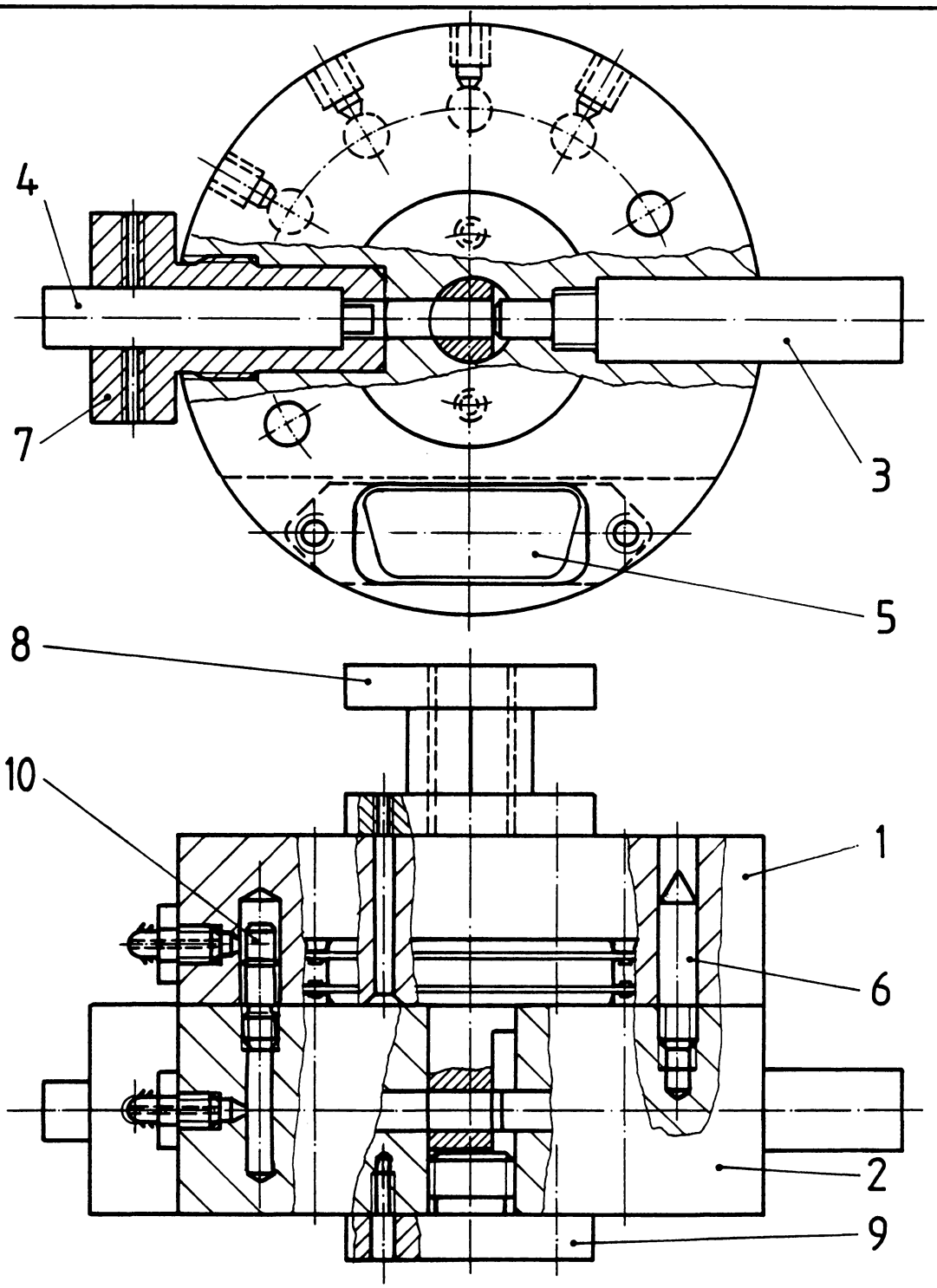
The functional specifications, considered to be important for the successful implementation of this system are listed below:

1. Coupling stiffness must be reached.
2. The robot's payload is 22 lb. The same capacity is required for the quick change mechanism.
3. There must be at least six 1/4 inch diameter fluid channels (100 psi).
4. There must be at least 24 electronic channels.
5. Full rotational capability of fluid and electrical lines must be reached.
6. The physical dimensions of the quick change mechanism are to be minimal.
7. Mating must be reliable.

The mechanical design consists of an upper body mounted to the robot wrist and a lower body attached to the end effector. The upper body contains the locking mechanism and acts as a manifold for the pneumatic fluids. The mechanism is 3.5 inches in diameter, 2.25 inches in length and has a weight of 3.5 lbs. (See Figure 4.2).

The locking/unlocking mechanism meets demanding requirements outlined above and it is robust. It locks and unlocks with exceptional reliability and operates on shop air (45 psi).

The quick change interface has 24 electrical, 2 pneumatic, and 2 vacuum lines connected by means of the adapters, permitting the tools to be controlled intelligently by the robot without cumbersome umbilical cords. The major difference between a robot quick change mechanism and a tool change mechanism for computer controlled machining centers is the robot's inability to perform rotational coupling techniques. This restriction is caused by the need for fluid and electrical coupling devices. Some of the commercially available quick change systems (EOA Applied Robotics, Intelledex, Incorporated, etc.) employed extremely complicated and complex interchange mechanisms for their systems. This results in difficult machining processes and high production costs. The quick change adapters developed in this research couple by fitting over the end effector locking pin on the tool mounting plate (lower body) (1). While fitting over the end effector locking pin, the adapter is also guided by the two indexing pins (6).



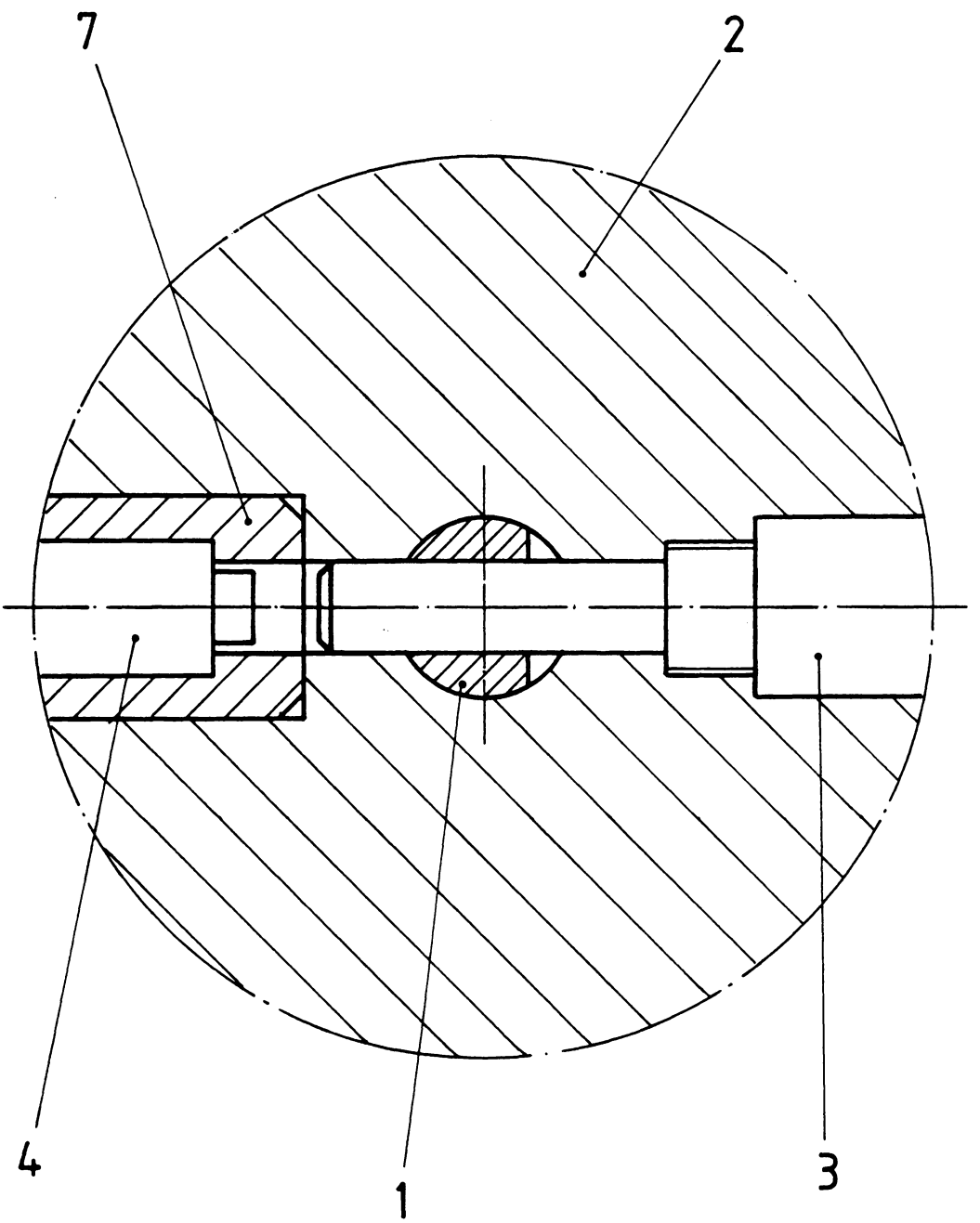
	Name	Date	Scale: 1:1	
Work				
Check				

Figure 4.2 Quick Change

As a result, the adapter achieves a precise fit on the tool mounting plate. The indexing pins are used not only to assure a reliable coupling process, but also to absorb any applied torque. The air cylinder (3) is actuated by a DO (digital output) point and extends fully to lock both adapters so that the coupling process is completed successfully as shown in Figure 4.3. Even significant positional and repeatability deviations in the range of 0.2 inches or 5 degrees are absorbed by the mechanism, and reliable coupling is still guaranteed. The unlocking sequence is established through the deactivating of cylinder (3) and the activating of cylinder (4) to reposition the locking rod.

The longitudinal inaccuracy is less than 0.01 inches and satisfies the demand of even complex and complicated applications. The rotational inaccuracy was not evaluated because of the lack of high precision sensing and measurement equipment for this research. However, an empirical investigation revealed that the system is not restricted by rotational inaccuracy.

The mating and detaching forces, required to fit the adapter over the end effector locking pin and the fluid connectors are relatively strong. At 4 lbs., they have almost reached the maximum allowable level for small assembly robots with 5 lbs. pull and/or push capacity. Unfortunately these mating forces are necessary because of the high precision standards and the friction required between the fluid connectors to guarantee a secure seal.



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Work				
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Figure 4.3 Locking Mechanism

Additional tests indicated that the electrical connectors (5) are responsible for at least one-third of the friction forces. The aluminum face plate (8) was designed to allow the gripper to be parked reliably in the storage carousel.

The maximum payload can be calculated as follows [13]:

$d^3 = M_b * (0.1 * Q_b)^{-1} \quad ==> \quad M_b = d^3 * 0.1 * Q_b$

$M_b = (6.35\ mm)^3 * 0.1 * 90.0\ N * mm^{-2}$

$M_b = 2304.43\ N\ mm$

d = locking piston diameter

M_b = moment of flexion

Q_b = safety bending stress

$F = 2 * M_b * (1/2 + s/2)^{-1}$

$F = (2 * 2304.43\ N\ mm) * (6.35 + 3.18\ mm)^{-1}$

$F = 483.62\ N$

$P = F/f$

$P = 483.62\ N\ /\ 1.5$

$P = 322.42\ N$

==> applicable payload = 450 lb

F = applicable shearing forces

M_b = moment of flexion

l : see Figure 4.4

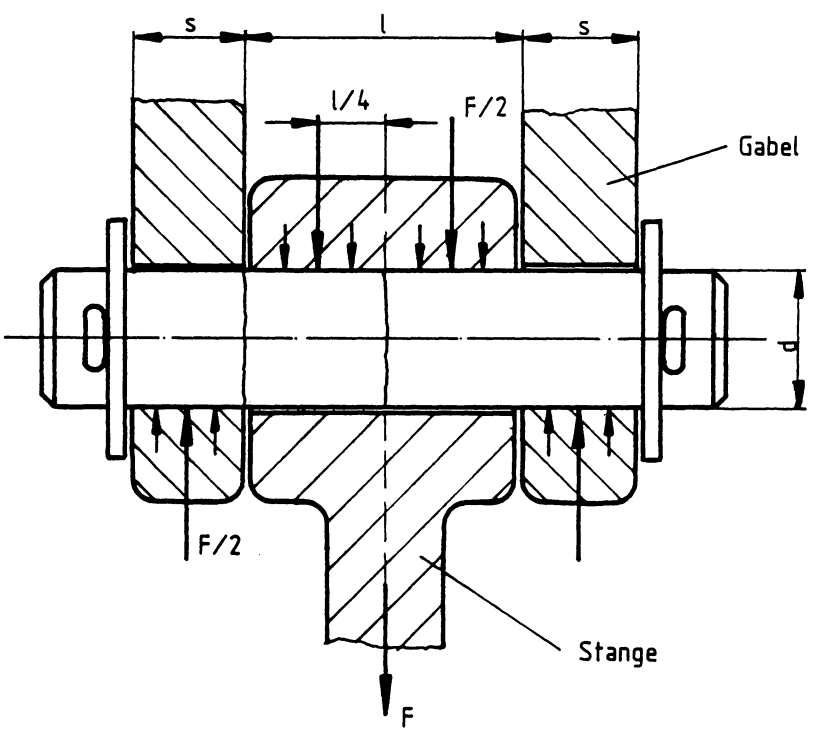
s : see Figure 4.4

f = safety factor

P = payload value

The self-coupling TRW cinch ribbon-solder type connector is used as the electronic interface. The mating requirements are in the approximate area of +/- 0.1 inch of allowable error in X and Y axis. Even the mating depth can vary in the range of less then or equal to 1/4 inch.

The pneumatic and the vacuum connectors have machine threads rather than pipe threads, so that they can be located accurately in all three dimensions. To reduce the mating forces, the female fluid connectors were tapered slightly so that the sealing contact occurs only in the last phase of the mating process. During the test and implementation phase, no leakage was ascertained.



	Name	Date		
Work			Figure 4.4 Calculation Explanation	
Check				

A sensor can be applied to measure the pneumatic pressure to alert the operator in the case of pressure leakage, which could affect the process significantly. If pressure is lost, a reliable performance is no longer guaranteed because it is possible that the spring loaded cylinder (3) will retract and unlock the quick change adapter. Under normal circumstances, the quick change will not be unlocked because of a decrease in pressure, since the static friction forces are larger than the spring forces. However, vibrations and frequent motion will cause the rod to work itself loose and retract. Two possible alternatives can be applied to guarantee a reliable performance even in case of pressure loss:

1. The above mentioned sensor can be used to stop the process and alert the operator.
2. Cylinder (2) can be replaced by a double acting cylinder. In this case, not only problems resulting from decreasing pressure can be resolved, but also cylinder (3) would no longer be needed because a double acting cylinder can retract without external support.

If a double acting cylinder were to be used, the machining process would be easier and less time consuming, i.e. the quick change would have even higher economic justification. The latter alternative was not used for this research, owing to its extremely compact organizational framework and to the long waiting periods involved in delivering these parts. Even if a double acting cylinder were in use,

a pressure sensor would still be irreplaceable because a loss of pressure could still cause significant damage. If the cylinder does not retract fully and the quick change attempts to change grippers, the adapter would not be unlocked.

Before the system was implemented, a series of tests was conducted to explore its design weaknesses. The quick change adapters were coupled manually, and the cylinder (3) was extended. In 47 out of 50 trials, the locking mechanism failed to lock the upper and lower body correctly. In further evaluations it was found that this extremely low percentage of fault free performance was caused by the cylinder's highly concentric tolerance. In additional investigations, it was established that the problem was easily solved by putting an "O-Ring" between quick change adapter and cylinder shoulder to compensate the concentric tolerance. Later tests proved this theory with a fault free continuous performance for 50 cycles. The detaching cylinder (4) has a significantly smaller rod diameter. Its performance is not hindered by friction forces, i.e. the piston retracts without the need of external support.

Final manual tests verified a fully reliable system performance for the whole cycle, including the unlocking sequence. All design requirements were fulfilled, and a successful implementation with the appropriate gripper was reached. Further research could be done to reduce the devices' physical dimensions and their relatively heavy weight (3.5 lbs.) to make them better applicable for very small

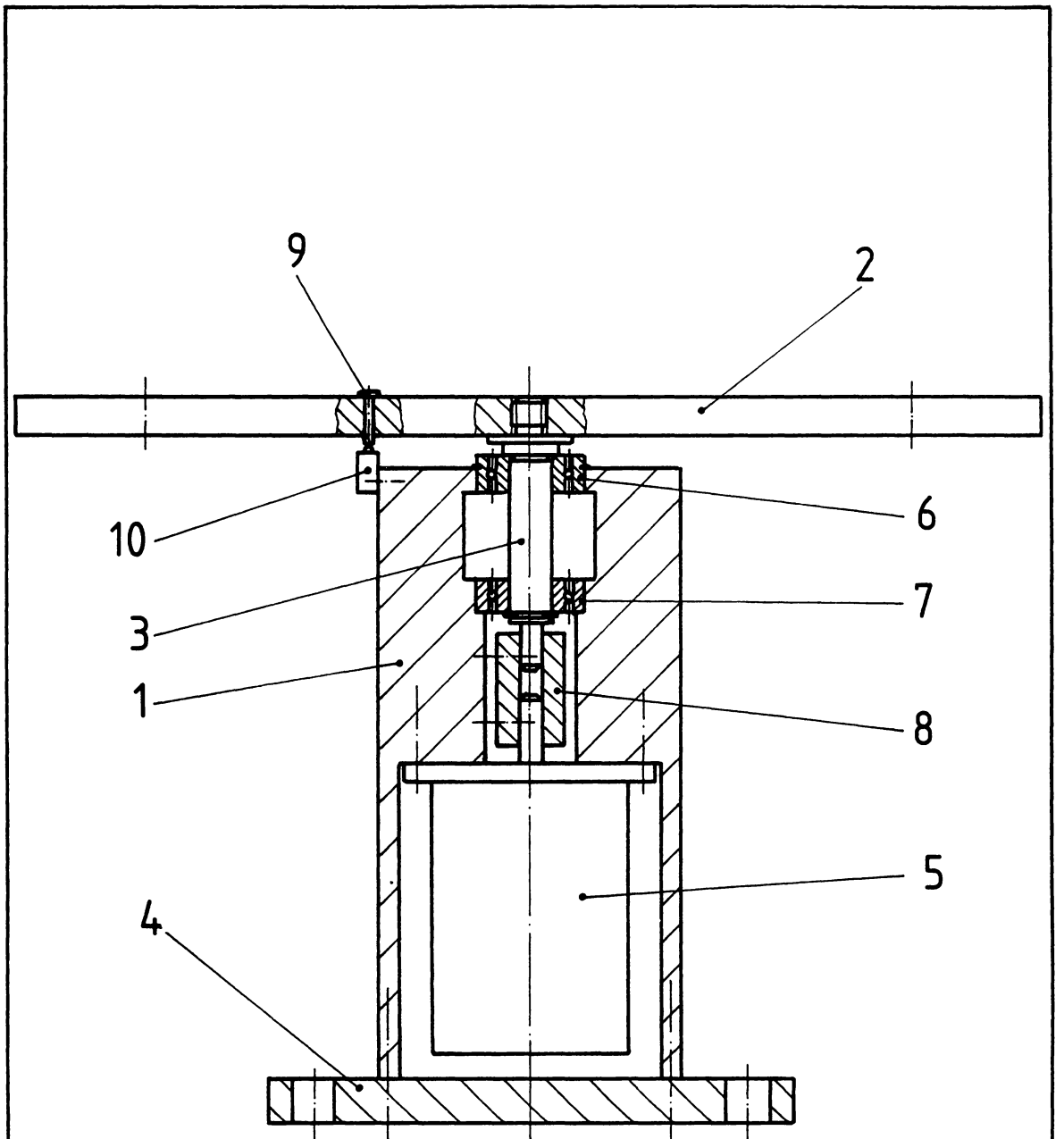
assembly robots. If the basic construction material were changed from aluminum to plastic, a significant weight reduction could be achieved. The loss of resistance and payload capacity, however, would have to be taken into consideration. Since the current payload capacity with aluminum is 20 times higher than the required payload, a significant reduction is acceptable.

4.3 Carousel Design

To add a high degree of flexibility, the carousel was designed to equip the robot workcell with a storage system containing four different types of grippers. The following design objectives were considered necessary for a gripper carousel:

1. To take at least four grippers.
2. To locate the grippers to be picked up precisely.
3. To be of simple construction.
4. To be space efficient.
5. To keep the grippers from sliding out of the holster.
6. To tolerate at least 1/8 inch of gripper displacement in x,y and z axis during the parking process.
7. To have repeatability of alignment.

The carousel consists of 10 parts as shown in Figure 4.5. The largest diameter is 12 inches and the overall length is 8.25 inches.



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Work				
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Figure 4.5 Gripper Carousel

The steel shaft (3) runs on bearings (6), (7), is screwed into the aluminum table (2) and is driven by the "Slo Syn" stepper motor (5). The aluminum bottom plate (4) is bolted to the robot work table to provide a firm base for the aluminum body (1). Stepping motor (5) and shaft (3) are connected by a brass coupler (8).

The stepper motor-driven system rotates counter clockwise due to the configuration of the electrical interface. The rotational accuracy is limited by the stepping motor resolution. To complete one revolution, 200 pulses must be sent to the stepper. This implies that the tolerance cannot be less than 360/200 degrees. The plastic stop (9) actuates the switch button (10) every time the table arrives at the home position. After the home position has been reached and the switch button been actuated, any called location can be attained with a relatively high degree of repeatability.

The four gripper holsters were designed to cope with a significant degree of displacement during the parking process. Although the parking tolerance can be large, the grippers' fit in the holster provides for accurate positioning with high repeatability. The gripper quick change face plate is fastened by means of a surfacing pin with ball point and a form fit to guarantee the required positioning reliability and to be certain that vibration and carousel motion do not displace the parked grippers. The robot DO (digital output) signals are transmitted to a stepper driving card to create the squared pulses necessary to drive the stepping motor. The use of

manual relays caused some interesting problems which were accompanied by contact bounce and a noisy electronic environment.

Selection of the bearings and the shaft diameter was based on the following calculations [13]:

Shaft:

given: d = 0.5 inches = 12.7 mm

max. pulling or pushing force = 22 lbs = 10kg

$\Rightarrow F = 10kg * 10\ m\ sec^{-2} = 100\ N$

$Q_{0.2} = 300\ N\ mm^{-2}$

$M_b = F * a;\ a = 5.5\ inch = 139.7\ mm$

$M_b = 100\ N * 139.7\ mm = 13970\ N\ mm$

$R_t = 4 * 10^{-6}\ m \Rightarrow b_1 = 0.98$

$v = 1.5$

$K = 420\ N\ mm^{-2}$

$Q_z = K * b_1 * v^{-1} = 420 * 0.98 * 1.5^{-1}\ N\ mm^{-2}$

$= 274.40\ Nmm^{-2}$

$W_a = 3.14 * d^3 / 32 = 200.99\ mm^3$

$Q_b = M_b * B_k / W_a$

$B_k = 1.5 \Rightarrow Q_b = 229.37\ Nmm^{-2}$

$Q_b < Q_z$

double check: $d = (M_b / 0.1 * Q_z)^{1/3} = 10.84\ mm$

$\Rightarrow$ shaft diameter > 10.84 mm

a = distance between load and center

d = shaft diameter

F = peak load

K = fatigue strength under repeated bending stress

M_b = moment of flexion

R_t = surface roughness

v = safety factor

Q_b = bending stress

$Q_{0.2}$ = proof limit

Q_z = safety load

W_a = section modulus

B_k = stress concentration factor

The constant torque T [13], required to turn a shaft with inertia I_x (ft - lb - sec) from rest through an angel A (in degrees) in time t (sec) is:

$T = 0.035 * I_x * D * t^{-2}$

$A = 90^o$

t = 2.0 sec.

$I_x = 0.00388 * W * d^2$

Shaft: d = 12.7 mm = 0.042 ft

l = 152.4 mm

$V = d^2 * 3.14 * l/ 4 = 19305.56 \text{ mm}^3 = 19.305 \text{ cm}^3$

$W = e * V = 7.89 * 10^{-3} * 19.305 \text{ cm}^3 * \text{kg cm}^{-3}$

$= 0.15 \text{ kg} = 0.34 \text{ lb}$

$\Rightarrow I_{x1} = 0.00388 * 0.34 * (0.042)^2$ lb - ft - sec^2

$= 2.3 * 10^{-6}$ lb - ft - sec^2

Table: d = 304.8 mm = 1.0 ft

l = 12.7 mm

V = 926.67 cm^3

$W = e * V = 2.7 * 10^{-3} * 926.67\ cm^3 * kg\ cm^{-3}$

= 2.5 kg = 5.56 lb

$I_{x2} = 2.2 * 10^{-3}$ lb - ft - sec^2

Grippers: Since the grippers are located around the table's inside edge, their inertia can be assumed to be equal to a thick-walled cylinder with inside diameter d = 0.42 ft and outside diameter D = 1.083 ft.

d = 0.42 ft

D = 1.083 ft

Gripper weight = 4 lb => 16 lb for all 4 grippers

$I_{x3} = 0.00388 * W * (d^2 + D^2)$

$= 0.00388 * 16 * ((.42)^2 + (1.083)^2)$

$= 8.36 * 10^{-2}$ lb - ft - sec^2

Summation of all I_x's:

$I_x = 0.106$ lb - ft - sec^2

$T = 0.035 * I_x * A * t^{-2}$

$= 0.035 * 0.106 * 90 * 2$ lb ft $sec^2 * sec^{-2}$

$= 0.0835$ ft lb

$= 16.03$ oz inch

T = constant torque

I_x = inertia

d = smaller diameter

D = larger diameter

l = length

W = weight

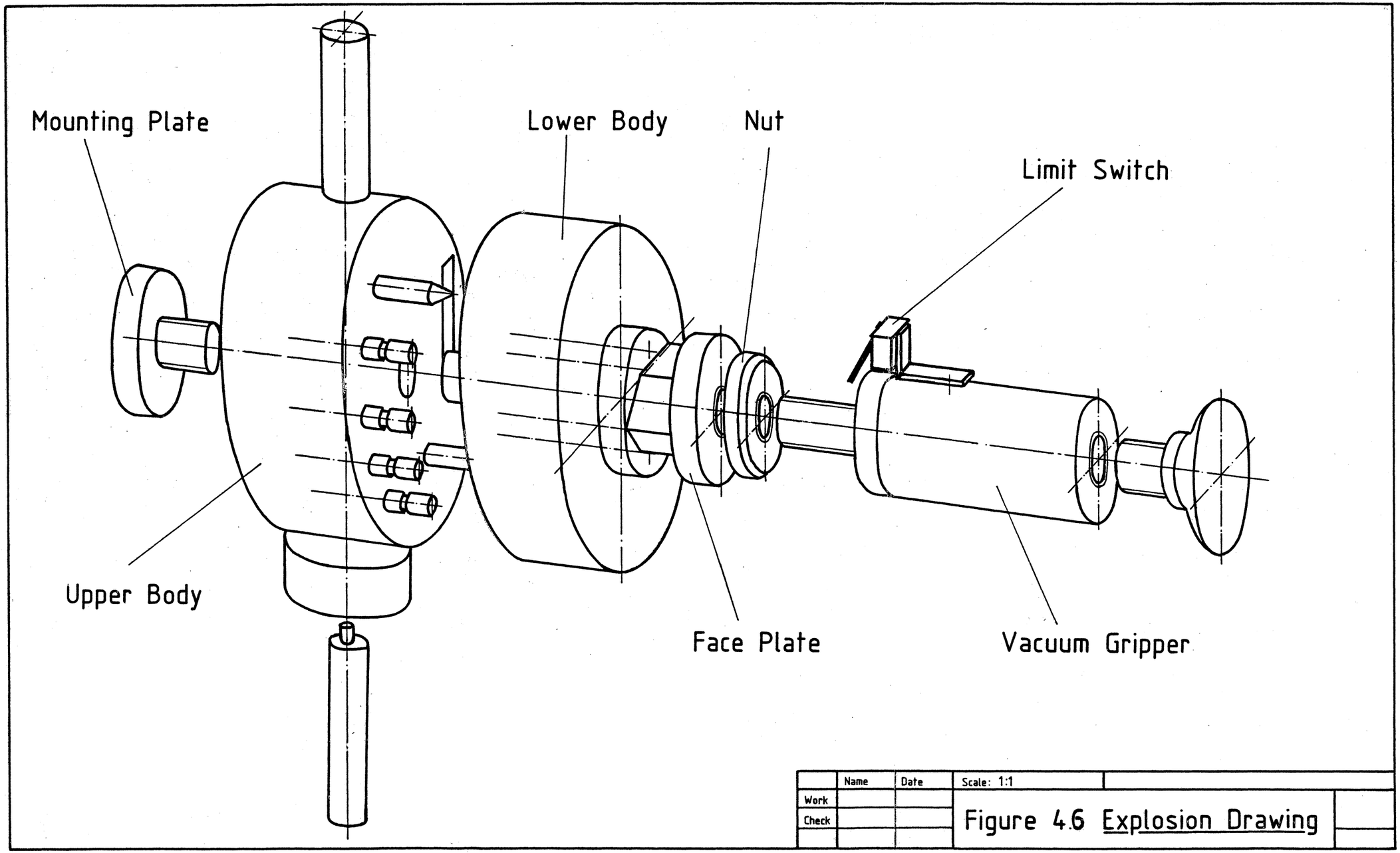
V = volume

t = time in which the table has to turn 90^o

A = Angle to be turned

The above calculations indicate that a stepping motor with a minimum static torque capacity of 16 oz-inch is required to turn the table equipped with 4 grippers 90 degrees within 2 seconds. A "Slo Syn" stepping motor with 45 oz-inch static torque capacity was chosen to satisfy the torque and design requirements. The torque capacity requirement was more than fulfilled, so that a subsequent implementation of heavy end of arm effectors would be permitted. The turn table location within the workcell was selected to be as space efficient as possible so as to provide a maximum of safety for man and machine. In an earlier stage of this study, it was planned to locate the carousel exactly at the home position to allow for good operator access and space efficiency. Since the robot always must move to the

home position before a new program or cycle can be initiated, the carousel was found to be an obstruction when long grippers were in use. The final carousel station assures a minimal possibility of collision, thus avoiding gripper and/or carousel damage. Additionally it is described to withdraw or replace end effectors by using linear motion to and from the desired holster.



	Name	Date	Scale: 1:1
Work			
Check			

Figure 4.6 Explosion Drawing

Chapter V

SYSTEM TESTING AND DEMONSTRATION

A series of tests was conducted to evaluate the performance and reliability of the software and hardware systems. During the implementation stage, certain testing procedures were carried out to isolate potential problem areas. The test procedures were similar to the procedures reported by Vranish [20].

5.1 Performance Testing

The quick change adapters were coupled manually, and the locking sequence was simulated by actuating the locking cylinder. It was found that of 50 trials, only 3 were completed satisfactorily. The locking mechanism was dismantled and each component was tested individually. All parts satisfied the demanding requirements fully, so that the extremely high rate of failure had to be related to the assembly process only. Additional examinations proved that the adapters' bottle-neck was caused by the cylinder's highly concentric tolerance. The problem was solved by placing an "O-Ring" between quick change adapter and cylinder shoulder to compensate for the concentric tolerance. The testing sequence as mentioned above was reconducted, which yielded a continuous, fault free performance.

During the second testing phase, the manual coupling process was

replaced by an automatic mating sequence. The lower quick change body was placed into the carousel manually, the turn table was fastened so as to avoid uncontrolled motion, and the robot was taught the correct pick up points in the teach mode. The pick up coordinates were down loaded to the test software which moved the robot to mating depth, actuated the locking cylinder and afforded the operator sufficient time to determine if both adapters were coupled correctly or not. After 15 seconds, the locking cylinder was deactuated, and the unlocking cylinder was actuated and deactuated again.

After an additional 15 seconds, the end of arm was moved in positive Z direction and the cycle was started again. All 50 cycles were completed fault free and without any loss of reliability. Then, the pick up coordinates were purposely modified in the software to evaluate the system's compliance to pick up location errors. The result of this testing phase was that even a rotational inaccuracy of 5 degrees and a displacement of +/- 0.2 inches in X and Y direction were tolerated without any negative impact on the coupling process.

Plus and minus tolerances in Z direction have a completely different influence on the system's performance. While plus tolerances (the mating depth is not reached fully) can only be permitted within the range of 0.003 inches, the system is much less sensitive for minus tolerances. The turn table shaft diameter was chosen to be 1/4 inch, so that the bending moment produced is strong enough to compensate minus tolerances in Z direction up to 1/4 inch, even though the

robot's pushing capacity is limited to 22 lbs.

The fluid connectors were not tested separately, but no leakage was ascertained during their use. Rotational and axial tolerances were not evaluated because of the lack of high precision measurement equipment. However, they were not found to be of significant importance.

An AML/E program was written to test the stepping motor performance when it received pulses from the controller output port. The software was set up to turn the table to the home position, to read the position switch status, and, depending on the value (1 or 0 for closed or open switch respectively), generate further pulses or interrupt the cycle for 10 seconds. After 10 seconds, 50 pulses were transmitted to turn the table 90 degrees. BRANCH statements were used to create an infinite loop, so that the performances in a 4 hour non-stop turning cycle could be evaluated. An interesting problem was discovered during the early implementation phase. Even though the software generated the correct number of pulses, and stepping motor and stepper drive card had been separately tested and proven to be fault free, the carousel turned clockwise or counter-clockwise, in an uncontrolled manner, thereby rendering an unacceptable performance. An investigation of each of the system's components revealed that the problem had not been caused by the stepping motor, the stepper drive card, or any of the electrical contacts.

WRITEO and DELAY statements were used to create the pulses to be sent to the stepper drive card from the controller output port. The following sequence of commands were used to create one pulse:

```
WRITEO (DO 16, OFF);     -- Open output port 16
DELAY (0.1);             -- Delay 0.1 seconds
WRITEO (DO 16, ON);      -- Close output port 16
DELAY (0.1);             -- Delay 0.1 seconds
```

It was found that the established frequency of 5 Hz was not high enough to drive the appropriate stepping motor. The achieved frequency caused the undesirable system behavior that was being experienced.

Since a delay of 0.1 seconds is the smallest possible value in AML/E, 5 Hz is the natural upper boundary for the system. Different lower frequencies (2.5 Hz and 1 Hz) were tested but were found to be as useless as 5 Hz. Correspondingly the goal was to establish a system with more than 5 Hz. The idea of implementing a programmable controller or a micro processor to drive the motor was dismissed to keep the system as straightforward as possible. Further evaluations proved that the mechanical controller output relay caused some additional problems with its contact bounce.

Redesigning the stepper drive card allowed the use of contact bounce to create a pulse frequency of 10 Hz without any software changes. The implementation of the contact bounce established a system

performance of complete reliability and made it twice as fast as its original version with 5 Hz. The testing loop was initiated again, and a fault free, four-hour, non-stop cycle was completed.

The last sequence of tests was set up to appraise the logical and mechanical coordination between robot, quick change adapter, carousel and software. The palletizing software was reduced to the basic gripper change sequence:

1. The end of arm moves above the carousel.
2. The carousel turns to the home position and revolves an additional 45 degrees to locate the heavy weight gripper.
3. The end of arm moves down to mating depth.
4. The adapters are locked.
5. The gripper is slid out of its holster.
6. The gripper is parked again.
7. The adapters are unlocked.
8. The end of arm moves above the pickup location.
9. The end of arm moves to a known position.

In an early testing phase, the software was set up so that the carousel first located the gripper in the pickup position before the robot moved over to adapt the gripper. In this configuration, it was discovered that each time the end of arm moved, the carousel started shaking, and turning, and failed to reach the required degree of accuracy. Signals, sent by the controller to move the end of arm were

partially transmitted to the stepper control circuit creating a noisy electrical environment. To avoid gripper displacement in the pickup phase, the software was modified so that the end of arm was located first, and then the carousel turned the appropriate number of steps. One of the interesting determinations of this test sequence is that end of arm Z moves do not create a noisy environment, i.e. they do not affect the carousel performance or its accuracy in any way. So that a fault free cycle is guaranteed, the final software package was established to locate the appropriate gripper in the pickup position after all end of arm moves have been completed, even though the gripper holster might already have been in the correct position. Two hundred fault free gripper change and pickup cycles (described above) proved the system to be reliable and advanced enough to satisfy industrial demanding requirements.

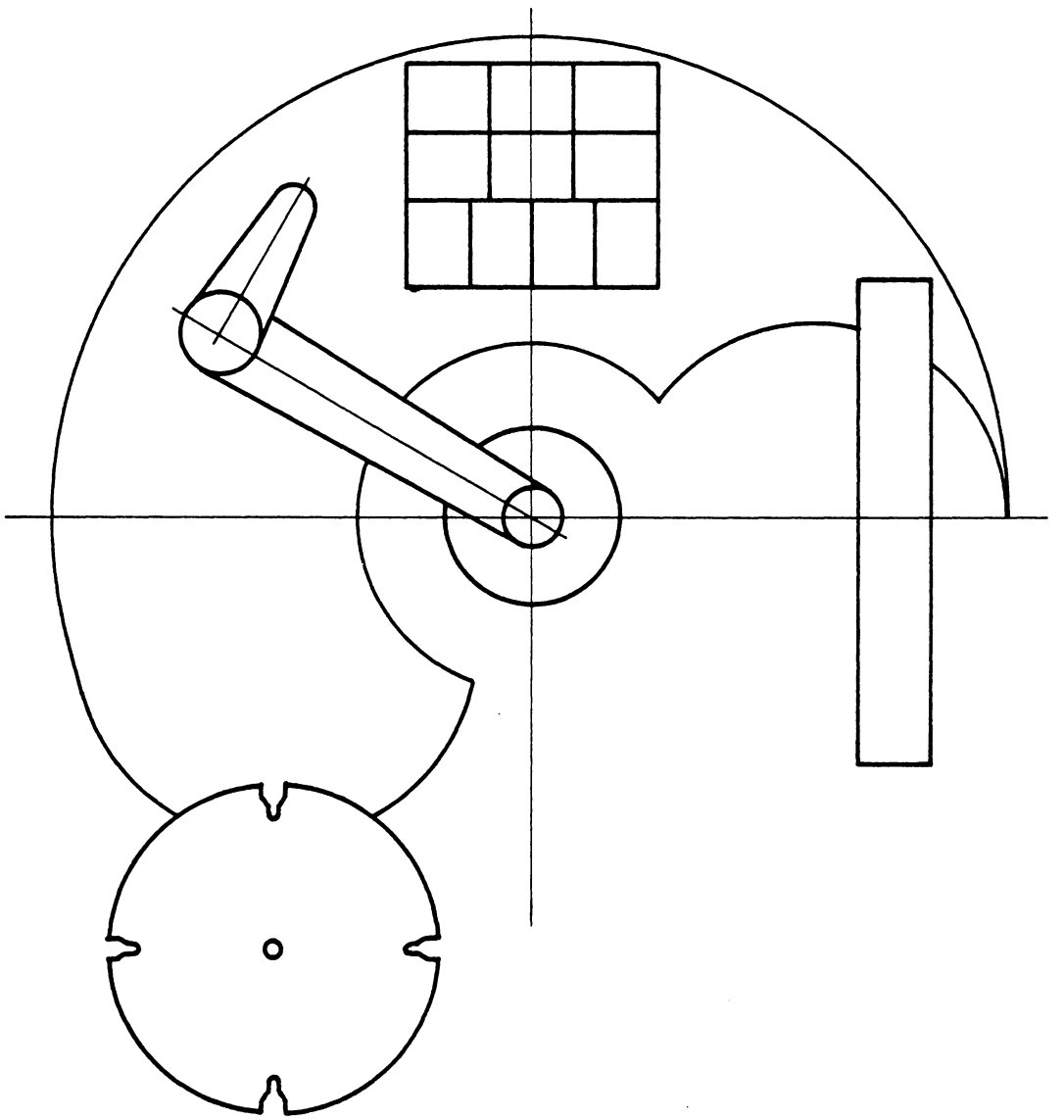
Table 5.1 Test Summary

Test	Results
50 locking cycles with manual coupling	3 fault free cycles
50 locking cycles with manual coupling, after compensating the cylinder's tolerance	50 fault free cycles
50 locking cycles with automatic coupling	50 fault free cycles
10 carousel positioning cycles with 5 Hz pulse frequency	no satisfying result
2 carousel positioning cycles with 1 Hz pulse frequency	no satisfying result
4 hours (48 cycles) carousel positioning cycles with 10 Hz pulse frequency	fault free performance
200 automatic gripper change and pickup cycles	fault free performance

5.2 System Demonstration

The workcell was laid out to allow a high degree of efficiency in terms of used space, speed, and safety for the machine and the operator. The layout consists of the "7545 Manufacturing System" with the center coordinates X = 0, Y = 0, Z = 0, a "Fischer Technik" conveyor with pickup location coordinates X = 400, Y = 400, Z = -162, R = 0, a pallet (scale 1:5) with lower left corner coordinates X = -244.0, Y = 300.0, Z = 20.0, R = 0, a quick change adapter mounted to the robot wrist, a vacuum gripper mounted to the quick change, and a carousel gripper storage with pickup coordinates X = -401.0, Y - 318.3, Z = -214.6, R = 54,0. (See Figure 5.1). Since neither dunnage nor a mechanical gripper were available, the demonstration was given within the following system environment:

1. One special purpose vacuum gripper with limited intelligence.
2. One complete quick change mechanism with two adapters (lower and upper body).
3. A "Fischer Technik" conveyor with limited intelligence.
4. A complete stepping motor-driven carousel with four gripper holsters.
5. A 9.6 inches by 8.0 inches pallet.
6. Thirty wooden blocks, serving as substitutes for real boxes with inch dimensions of 3.2 by 2.4 by 0.5 respectively weighing 0.2 lbs.



	Name	Date		
Work				
Check				

Figure 5.1 Robot Work Cell

The quick change lower body with vacuum gripper was placed into the low weight gripper holster manually, and the carousel was turned to an arbitrary position. The robot was powered on, connected to the PC, in automatic mode, returned to the home position, and placed on line. The software user disk was put into the IBM PC's disk drive A and the AML/E system disk into drive B. The PC was boot loaded causing the autoexecutable file to start the user program. As soon as the environment was specified by the operator, the AML/E program for the optimal interlock pattern was generated, compiled and loaded to the robot controller. The operator initiated the cycle by pressing the APPLICATION I button and the START CYCLE button. The robot's end of arm moved above the carousel, the carousel was turned to the proper holster, the end of arm picked up the gripper, moved over to the conveyor and grasped a waiting box. While the robot sat the box in its appropriate place on the pallet, the conveyor brought the next box into the pickup location, where it signaled its presence by pressing a limit switch. The robot moved over to the conveyor, grasped the next box, the conveyor was started again, and the box was placed on the pallet. When the first layer had been completed, the whole sequence was repeated with a pallet pattern, turned 180 degrees. The third and final layer was stacked in a pattern identical to the first layer. As soon as the pallet had been stacked to capacity, the operator attention horn was sounded. After 30 seconds, the end of arm moved in front of the carousel, the low weight gripper holster was located correctly, and the gripper was slid into the holster. The unlocking sequence was followed by a fast move back to the home position, where

the operation was stopped when the emergency button was pressed.

When two boxes with larger width dimensions were to be stacked side by side, it frequently happened that the problem of overlap between these two boxes occurs so that pasteboard shippers would have been damaged. If, in a real application, boxes with significant tolerances must be stacked, two possible solutions to the problem can be applied:

1. The input data must be identical to the largest possible box dimension. This solution tolerates a relatively low pallet utilization.
2. The stacking sequence must be modified, so that the boxes are slid into the appropriate position on the pallet. This solution tolerates some boxes being pushed aside sightly and the inside pallet edges being overlapped.

Chapter VI

CONCLUSIONS AND RECOMMENDATIONS

The goal of linking material handling with flexible automation to create a combination of off-line and on-line programming was achieved and afterwards successfully implemented in a practical application. A complex demonstration underlined system uniqueness. Although certain aspects of this study have been examined by other researchers, there has been no similar composite study established.

6.1 Critique and Extensions

The implemented interlock heuristic and the combined heuristic provide a very high pallet utilization which exceeds the initially expected results. A heuristic like the "Two Dimensional Cutting Stock Problem Algorithm" [17] might have offered better solutions. Since the software was set up in a modular fashion, alternatives could be implemented later without changing the whole concept. Three extensions within the palletizing framework could be subject to further research in a succeeding project:

1. Implementation of bar code labels and reader.
2. Implementation of computer vision.
3. Providing multiple pallets.

The implementation of bar code labels and readers would make the system even more independent of operator intervention. Boxes could be labeled according to size and weight differently, and a bar code reader, mounted to the conveyor, could read the information for the current production batch. The bar code information could be transformed to the PC, and the interactive program phase could be handled automatically. The system described above would require operator intervention only when problems arise and at the beginning or the end of a shift. If on-line communication between bar code reader and PC were to be established, the PC would have to be tied to the system permanently. This is a disadvantage when compared to a system in which the PC is only used in the first phase of the process.

If differently sized boxes were not produced in batch sizes, but individually, production would have to be examined and sorted beforehand. Shippers of equal size and weight would have to be collected in buffer facilities and then sent into the system serial, or computer vision or bar code readers would have to be coupled to host computer communication. Each arriving box would have to be handled separately. Both solutions are quite complex and changes in production sequence should be considered so that a fundamental basis for succeeding automation is established to reach high economic justification. Computer vision could be used to determine the box sizes as they are transported on the conveyor and to recognize the precise pallet location. Even multiple pallets could be provided inside the workcell to avoid idle time. Another useful extension

would also be the introduction of a conveyor system for the pallets so that the operator would not have to enter the workcell at all.

The idea of using bar code labeling could also be employed to the quick change and carousel system so that grippers would not always have to be placed in the same holster. Since 10 Hz is the upper frequency limit for robot controller generated pulses, a programmable controller or even a microprocessor could improve the speed and system performance significantly. The microprocessor or programmable controller would be initiated by the robot controller. The pulses, however, would be generated externally.

The quick change adapter's performance is satisfying and reliable. But if the same locking mechanism were used, smaller and lighter system design might be possible to make the quick change better applicable to small assembly robots with very low pulling or pushing capacity. The introduction of plastic as basic construction material, the use of multiple small electrical connections instead of one large connector, and an overall diameter reduction could cause significant improvement in task fulfillment.

Microprocessor capabilities should be added to the quick change or to the different grippers, to establish a system consisting of as few approximations as possible. If grasping, pulling, pushing and tilting forces could be measured and transformed to the robot controller, a high degree of intelligence could be added to the system. Damage and

waste production could be recognized at an early stage or even be avoided.

The extension of the overall concept to non-palletizing operations as well as the linking to Artificial Intelligence could be considered. A classic non-palletizing robot application area is the paint spraying of fixed parts, especially in the automobile industry. If fixtures wear out, and parts are not located correctly, a fault free paint spraying process is no longer guaranteed. If parts to be sprayed are of various shapes or sizes, a large number of programs would have to be generated, compiled and loaded to the controller. If computer vision could be introduced to such a process, parts would not have to be fixed and ordered beforehand.

The spraying software could be generated dynamically, based on the vision systems input data. The whole production program could be recognized by the vision system. The problem of viewing only one surface of the part and then generating a three dimensional control program could be solved by introducing a kind of Expert System. Complex data bases would have to be generated previously, however economic justification could still be reached because of high and frequently changing production rates. Coupling the CAD system to data base generation would probably offer considerable support establishing Expert Systems.

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APPENDIX A

INTERLOCK PROGRAM

```
C     INTERLOCKPROGRAM
      INTEGER BLACK,BLUE,GREEN,CYAN,RED,MAGENTA,YELLOW
      INTEGER WHITE,BBLACK,BBLUE,BGREEN,BCYAN,BRED
      INTEGER BMAGENTA,BYELLOW,BWHITE,BLINK,HIGHINT
      INTEGER X,J,B,A1,C1,C2,Y,Z1,P,XP1,XP,XP3,XP4,XP5,TOT,A,Z,X1
      INTEGER X2,X3,X4,X5,X6,K,A2,A3,A4,A5,M,I,N,A6,A7,A8,A9,E
      INTEGER NN,IIJ,KK,JK,IJ,III,JJJ,LENGT,ATTRIB,PPR1,PPR2,PPR3
      INTEGER PPR4,N1,N2,N3,N4,WEIGHT,N1R,N2R,N3R,N4R,WW
      REAL LENGTH, WIDTH, HEIGHT, UTI, L, H, W,X7,XK,XL,LEFTX,LEFTY
      REAL RIGHTX,RIGHTY,UPRX,UPRY,PICKX,PICKY,PICKZ,PICKR,HFRAME
      REAL XBOX,XBOX1,YBOX,YBOX1,P1,P2,LO,WO,HO,XBOX2,XBOX3
      REAL ZMOVE,ZPICK,LLX1,LLX2,LLX3,LLX4,LLY1,LLY2,LLY3,LLY4
      REAL LRX1,LRX2,LRX3,LRX4,LRY1,LRY2,LRY3,LRY4,URX1,URX2,URX3,URX4
      REAL PICKX1,PICKY1,PT(100),X11,X22,X33,X44,DUZ(20),INTERX,INTERY
      REAL INTERZ,INTERR,SEMIX,SEMIY,SEMIZ,SEMIR,MATE,CARLX
      REAL CARLY,CARLZ,CARLR
      DOUBLE PRECISION M1(20,20)
      CHARACTER*70 STR1,STR6
      CHARACTER STR2(70),STR3(70),STR7(70),STR8(70)
      EQUIVALENCE (STR1,STR2(1))
      EQUIVALENCE (STR6,STR7(1))
      DATA BLACK,BLUE,GREEN,CYAN,RED,MAGENTA,YELLOW /0,1,2,3,4,5,6/
      DATA WHITE,BBLACK,BBLUE,BGREEN,BCYAN,BRED /7,0,16,32,48,64/
      DATA BMAGENTA,BYELLOW,BWHITE,BLINK,HINGHINT /80,96,112,128,8/
      L=244.00
      W=203.20
      LEFTX=-244.
      LEFTY=300.00
      RIGHTX=0.0
      RIGHTY=300.00
      UPRX=0.0
      UPRY=503.20
      HFRAME=20.0
      PICKX=400.00
      PICKY=400.00
      PICKZ=-162.00
      PICKR=0.0
      INTERX=-401.0
      INTERY=-318.3
      INTERZ=0.0
      INTERR=54.0
      SEMIX=-401.0
      SEMIY=-200.0
      SEMIZ=-212.0
      SEMIR=54.0
      MATE=-214.6
      CARLX=-401.0
      CARLY=-318.3
      CARLZ=-212.0
      CARLR=54.0
      X=0
```

```
      E=0
      J=0
      XK=0.0
      XL=0.0
      X1=0
      X2=0
      X3=0
      X4=0
      X5=0
      X6=0
      X7=0.0
      DO 1 K=1,20
      DO 1 L1=1,20
      M1(K,L1)=0
1     CONTINUE
      ATTRIB=WHITE + BBLUE
      CALL CLS(ATTRIB)
      CALL PRINT(10,15,'THIS PROGRAM CALCULATES AN INTERLOCK PATTERN'
     *,44)
      GOTO3
C*************************************************************************
C     QUERY USER FOR INPUT DATA
C*************************************************************************
2      CALL PRINT(10,19,'PLEASE MAKE SURE THAT LENGTH GREATER WIDTH',42)
3      CALL PRINT(13,21,'TYPE 1 IF YOU WANT THE INPUT IN INCHES',38)
C*************************************************************************
C     DETERMINE WHETHER THE USER PREFERS TO WORK IN INCHES OR MM
C*************************************************************************
       CALL PRINT(15,22,'TYPE 0 IF YOU WANT THE INPUT IN MM',34)
       CALL PRINT(17,30,'ENTER OPTION  ==>',17)
      CALL INKEY(INCH,MM)
      IF(INCH.EQ.49)THEN
      CALL CLS(ATTRIB)
      CALL PRINT(10,22,'PLEASE GIVE WIDTH OF SHIPPER IN INCH',36)
      CALL PRINT(12,30,'ENTER OPTION  ==>',17)
      READ (*,*)WIDTH
      CALL CLS(ATTRIB)
      CALL PRINT(10,21,'PLEASE GIVE LENGTH OF SHIPPER IN INCH',37)
      CALL PRINT(12,30,'ENTER OPTION  ==>',17)
      READ (*,*)LENGTH
      CALL CLS(ATTRIB)
      CALL PRINT(10,21,'PLEASE GIVE HEIGTH OF SHIPPER IN INCH',37)
      CALL PRINT(12,30,'ENTER OPTION  ==>',17)
      READ (*,*)HEIGHT
      CALL CLS(ATTRIB)
      CALL PRINT(10,20,'PLEASE GIVE MAX. HEIGHT OF PALLET IN INCH',41)
      CALL PRINT(12,30,'ENTER OPTION  ==>',17)
      READ(*,*)H
      CALL CLS(ATTRIB)
      CALL PRINT(10,20,'TYPE 1 IF BOX WEIGHT IS IN THE RANGE OF',39)
      CALL PRINT(11,30,'0 - 5 lb.',9)
```

```
      CALL PRINT(15,20,'TYPE 0 IF BOX WEIGHT IS IN THE RANGE OF',39)
      CALL PRINT(16,30,'5 - 10 lb.',10)
      CALL PRINT(18,30,'ENTER OPTION  ==>',17)
      READ(*,*)WEIGHT
      CALL CLS(ATTRIB)
      CALL PRINT(10,20,'TYPE 1 IF THE PALLET SHALL BE STACKED',37)
      CALL PRINT(12,25,'WITH DUNNAGE, ELSE TYPE 0',25)
      CALL PRINT(14,30,'ENTER OPTION  ==>',17)
      READ (*,*)DUNYES
      IF(DUNYES.EQ.1)THEN
      CALL CLS(ATTRIB)
      CALL PRINT(10,20,'PLEASE GIVE THICKNESS OF DUNNAGE IN INCH',40)
      CALL PRINT(12,30,'ENTER OPTION  ==>',17)
      READ(*,*)THICK
      ENDIF
*************************************************************************
C     TRANSFORMING INCHES INTO MM
*************************************************************************
      WIDTH=WIDTH*25.4
      LENGTH=LENGTH*25.4
      HEIGHT=HEIGHT*25.4
      H=H*25.4
      THICK=THICK*25.4
      ELSE
      CALL CLS(ATTRIB)
      CALL PRINT(10,18,'PLEASE GIVE WIDTH OF SHIPPER IN MM',34)
      CALL PRINT(12,30,'ENTER OPTION  ==>',17)
      READ (*,*)WIDTH
      CALL CLS(ATTRIB)
      CALL PRINT(10,19,'PLEASE GIVE LENGTH OF SHIPPER IN MM',35)
      CALL PRINT(12,30,'ENTER OPTION  ==>',17)
      READ(*,*)LENGTH
      CALL CLS(ATTRIB)
      CALL PRINT(10,19,'PLEASE GIVE HEIGTH OF SHIPPER IN MM',35)
      CALL PRINT(12,30,'ENTER OPTION  ==>',17)
      READ (*,*)HEIGHT
      CALL CLS(ATTRIB)
      CALL PRINT(10,19,'PLEASE GIVE HEIGTH OF SHIPPER IN MM',35)
      CALL PRINT(12,30,'ENTER OPTION  ==>',17)
      READ(*,*)H
      CALL CLS(ATTRIB)
      CALL PRINT(10,20,'PLEASE GIVE MAX. HEIGHT OF PALLET IN MM',39)
      CALL PRINT(12,30,'ENTER OPTION  ==>',17)
      CALL CLS(ATTRIB)
      CALL PRINT(10,20,'TYPE 1 IF BOX WEIGHT IS IN THE RANGE OF',39)
      CALL PRINT(11,30,'0 - 5 lb.',9)
      CALL PRINT(15,20,'TYPE 0 IF BOX WEIGHT IS IN THE RANGE OF',39)
      CALL PRINT(16,30,'5 - 10 lb.',10)
      CALL PRINT(18,30,'ENTER OPTION  ==>',17)
      READ(*,*)WEIGHT
      CALL CLS(ATTRIB)
```

```
      CALL PRINT(10,20,'TYPE 1 IF THE PALLET SHALL BE STACKED',37)
      CALL PRINT(12,25,'WITH DUNNAGE, ELSE TYPE 0',25)
      CALL PRINT(14,30,'ENTER OPTION  ==>',17)
      READ (*,*)DUNYES
      IF(DUNYES.EQ.1)THEN
      CALL CLS(ATTRIB)
      CALL PRINT(10,20,'PLEASE GIVE THICKNESS OF DUNNAGE IN MM',37)
      CALL PRINT(12,30,'ENTER OPTION  ==>',17)
      READ(*,*)THICK
      ENDIF
      ENDIF
      IF(WIDTH.GT.LENGTH)GOTO 2
      IF(W.GT.L)GOTO 2
*************************************************************************
C     INTERLOCKING ALOGRITHM BEGINNS
*************************************************************************
      L0=L
      W0=W
      B=INT(H/HEIGHT)
4     X=X+1
      A1=INT(W0/LENGTH)
      IF(A1.GT.20)A1=20
      C1=INT(L0/WIDTH)
      C2=INT(L0/LENGTH)
      DO 5 A=A1,1,-1
      M1(A,J+1)=X
      M1(A,J+2)=A
      M1(A,J+3)=B
      M1(A,J+7)=B
      M1(A,J+4)=C1
      M1(A,J+5)=A*B*C1
      M1(A,J+8)=C2
      M1(A,J+6)=INT(((W0-(REAL(A)*LENGTH))/WIDTH)+.05)
      M1(A,J+9)=M1(A,J+6)*B*C2
      IF(M1(A,J+9).EQ.0)M1(A,J+5)=0
      IF(M1(A,J+5).EQ.0)M1(A,J+9)=0
5     CONTINUE
      IF(A1.NE.0)GOTO6
      CALL CLS(ATTRIB)
      CALL PRINT(10,20,'THERE ARE NO POSSIBLE INTERLOCK PATTERN',39)
      GOTO 170
6     IF(X.EQ.1)THEN
      J=9
      L0=W0
      W0=L0
      GOTO4
      ENDIF
      DO 7 X=1,20
      M1(X,19)=M1(X,5)+M1(X,9)
      M1(X,20)=M1(X,14)+M1(X,18)
7     CONTINUE
```

```
      DO 9 Z=1,30
      Y=1
      Z1=0
      A=M1(1,19)
      B=M1(1,20)
      IF(A.LT.B)THEN
      Z1=9
      A=B
      ENDIF
      DO 8 X=2,20
      IF(M1(X,19).GT.A)THEN
      A=M1(X,19)
      Y=X
      Z1=0
      ENDIF
      IF(M1(X,20).GT.A)THEN
      Z1=9
      Y=X
      A=M1(X,20)
      ENDIF
8     CONTINUE
      P=M1(Y,Z1+1)
      XP1=M1(Y,Z1+2)
      XP2=M1(Y,Z1+4)
      XP3=M1(Y,Z1+6)
      XP4=M1(Y,Z1+8)
      XP5=M1(Y,Z1+2)*M1(Y,Z1+4)+(M1(Y,Z1+6)*M1(Y,Z1+8))
      P1=(M1(Y,Z1+2)*M1(Y,Z1+4))+(M1(Y,Z1+6)*M1(Y,Z1+8))
      P2=LENGTH*WIDTH*HEIGHT*REAL(M1(Y,Z1+3)*100)
      XL=(XP1*XP2+XP3*XP4)
      IF(XL.GT.XK)THEN
      XK=(XP1*XP2+XP3*XP4)
      X1=XP1
      X2=XP2
      X3=XP3
      X4=XP4
      X5=XP5
      X6=((X1*X2+X3*X4)*INT((H/HEIGHT)+.5))
      X7=((X1*X2+X3*X4)/(L*W/(WIDTH*LENGTH)))*100.00
      ENDIF
      IF(Z1.EQ.0)M1(Y,19)=0
      IF(Z1.EQ.9)M1(Y,20)=0
9     CONTINUE
*************************************************************************
C     PRINTING THE VALUES OF: X1,X2,X3,X4,UTILIZATION, THE # OF
C     SHIPPERS PER LAYER, AND THE TOTAL # OF SHIPPERS ON THE PALLET.
*************************************************************************
      CALL CLS(ATTRIB)
      WRITE(*,10)X1
10    FORMAT(1X,'X1=',1X,I7)
      WRITE(*,11)X2
```

```
11  FORMAT(1X,'X2=',1X,I7)
    WRITE(*,12)X3
12  FORMAT(1X,'X3=',1X,I7)
    WRITE(*,13)X4
13  FORMAT(1X,'X4=',1X,I7)
    WRITE(*,14)X5
14  FORMAT(1X,'TOTAL NUMBER OF SHIPPER PER LAYER=',1X,I7)
    WRITE(*,15)X6
15  FORMAT(1X,'TOTAL NUMBER OF SHIPPER ON PALLET=',1X,I7)
    WRITE(*,16)X7
16  FORMAT(1X,'PALLET UTILIZATION=',1X,F5.2,1X,'PERCENT')
*************************************************************************
C   DETERMIN THE Z VALUE OF EVERY LAYER ON THE PALLET
*************************************************************************
    ZMOVE=-250+(HFRAME+HEIGHT)
    IF(X1.EQ.1)THEN
*************************************************************************
C   CREATING AN ARTIFICIAL EXTRA ROW IF INITIAL PALLET CONSISTS OF
C   ONLY ONE ROW
*************************************************************************
    X11=2
    ELSE
    X11=X1
    ENDIF
    IF(X2.EQ.1)THEN
    X22=2
    ELSE
    X22=X2
    ENDIF
    IF(X3.EQ.1)THEN
    X33=2
    ELSE
    X33=X3
    ENDIF
    IF(X4.EQ.1)THEN
    X44=2
    ELSE
    X44=X4
    ENDIF
*************************************************************************
C   DETERMINING THE LOWER LEFT, LOWER RIGHT, UPPER RIGHT CORNER
C   SHIPPER CENTER POINTS FOR ALL 4 POSSIBLE PALLET CONFIGURATIONS
*************************************************************************
    LLX1=-64.0+LENGTH/2
    LLY1=290.+WIDTH/2
    LRX1=180-LENGTH/2
    LRY1=LLY1
    URX1=LRX1
    URY1=LRY1+(X3-1)*WIDTH
    N1=X33*X44
    N1R=X3*X4
```

```
      PPR1=X4
      LLX2=-64.0+WIDTH/2
      LLY2=URY1+(LENGTH/2)+(WIDTH/2)+5.5
      LRX2=180-(WIDTH/2)+10.
      LRY2=LLY2
      URX2=LRX2
      URY2=LRY2+(X1-1)*LENGTH+9.0
      N2=X11*X22
      N2R=X1*X2
      PPR2=X2

      LLX3=LLX2
      LLY3=290.+LENGTH/2+5.5
      LRX3=LRX2
      LRY3=LLY3
      URX3=LRX3
      URY3=LRY3+(X1-1)*LENGTH
      N3=X11*X22
      N3R=X1*X2
      PPR3=X2

      LLX4=LLX1
      LLY4=URY3+(LENGTH/2)+(WIDTH/2)
      LRX4=LRX1
      LRY4=LLY4
      URX4=LRX4
      URY4=LLY4+(X3-1)*WIDTH
      N4=X33*X44
      N4R=X3*X4
      PPR4=X4
*************************************************************************
C     OPENING THE AML FILE FOR CREATING THE CONTROL PROGRAM
*************************************************************************
     OPEN(3,FILE='NEW.AML',STATUS='NEW')
*************************************************************************
C     DETERMINE THE # OF LAYERS
*************************************************************************
      LAYER=INT(H/HEIGHT+.5)
*************************************************************************
C     IF DUNNAGE IS REQUESTED, ADD HEIGHT OF DUNNAGE TO Z VALUE FOR
C     EACH LAYER
*************************************************************************
      IF(DUNYES.EQ.1)THEN
      DUNN=-1
      DO 18 I=1,LAYER
      DUNN=DUNN+1
      PT(I)=I*HEIGHT-250.+THICK*DUNN
18    CONTINUE
      ELSE
      DO 19 I=1,LAYER
      PT(I)=I*HEIGHT-250.+HFRAME
```

```
19  CONTINUE
    ENDIF
*************************************************************************
C   PUTTING Z VALUES INTO A STRING TO ZAP OF THE BLANKS
*************************************************************************
    DO 30 I=1,LAYER
    WRITE(STR1,20)I,PT(I)
20  FORMAT(1X,'Z ',I3,':',3X,'NEW',1X,F7.2';')
    IF(STR2(3).NE.' ')GOTO 26
    STR3(1)=STR2(1)
    STR3(2)=STR2(2)
    III=3
    DO 21 II =3,12
    IF(STR2(II).NE.' ')GOTO 22
21  CONTINUE
22  CONTINUE
    DO 23 JJ=II,60
    STR3(III)=STR2(JJ)
    IF(STR2(JJ).EQ.';')GOTO 24
    III=III+1
23  CONTINUE
24  CONTINUE
    WRITE(3,25)(STR3(KK),KK=1,III)
25  FORMAT(60A1)
    GOTO29
26  CONTINUE
    DO 27 III=1,60
    IF(STR2(III).EQ.';')GOTO 28
27  CONTINUE
28  CONTINUE
    WRITE(3,25)(STR2(KK),KK=1,III)
29  CONTINUE
30  CONTINUE
*************************************************************************
C   WRITE GLOBAL PALLET CONST. INTO AML FILE
*************************************************************************
    WRITE(3,31)LLX1,LLY1
31  FORMAT(1X,'LL1: NEW PT(',F7.2,',',F7.2,',0,90);')
    WRITE(3,32)LRX1,LRY1
32  FORMAT(1X,'LR1: NEW PT(',F7.2,',',F7.2,',0,90);')
    WRITE(3,33)URX1,URY1
33  FORMAT(1X,'UR1: NEW PT(',F7.2,',',F7.2,',0,90);')
    WRITE(3,34)N1
34  FORMAT(1X,'N1: NEW ',I3,';')
    WRITE(3,35)N1R
35  FORMAT(1X,'N1REAL: NEW ',I3,';')
    WRITE(3,36)PPR1
36  FORMAT(1X,'PPR1: NEW ',I3,';')
    WRITE(3,37)LLX2,LLY2
37  FORMAT(1X,'LL2: NEW PT(',F7.2,',',F7.2,',0,0);')
    WRITE(3,38)LRX2,LRY2
```

```
38  FORMAT(1X,'LR2: NEW PT(',F7.2,',',F7.2,',0,0);')
    WRITE(3,39)URX2,URY2
39  FORMAT(1X,'UR2: NEW PT(',F7.2,',',F7.2,',0,0);')
    WRITE(3,40)N2R
40  FORMAT(1X,'N2REAL: NEW ',I3,';')
    WRITE(3,41)N2
41  FORMAT(1X,'N2: NEW ',I3,';')
    WRITE(3,42)PPR2
42  FORMAT(1X,'PPR2: NEW ',I3,';')

    WRITE(3,43)LLX3,LLY3
43  FORMAT(1X,'LL3: NEW PT(',F7.2,',',F7.2,',0,0);')
    WRITE(3,44)LRX3,LRY3
44  FORMAT(1X,'LR3: NEW PT(',F7.2,',',F7.2,',0,0);')
    WRITE(3,45)URX3,URY3
45  FORMAT(1X,'UR3: NEW PT(',F7.2,',',F7.2,',0,0);')
    WRITE(3,46)N3
46  FORMAT(1X,'N3: NEW ',I3,';')
    WRITE(3,47)N3R
47  FORMAT(1X,'N3REAL: NEW ',I3,';')
    WRITE(3,48)PPR3
48  FORMAT(1X,'PPR3: NEW ',I3,';')

    WRITE(3,49)LLX4,LLY4
49  FORMAT(1X,'LL4: NEW PT(',F7.2,',',F7.2,',0,90);')
    WRITE(3,50)LRX4,LRY4
50  FORMAT(1X,'LR4: NEW PT(',F7.2,',',F7.2,',0,90);')
    WRITE(3,51)URX4,URY4
51  FORMAT(1X,'UR4: NEW PT(',F7.2,',',F7.2,',0,90);')
    WRITE(3,53)N4
    WRITE(3,52)N4R
52  FORMAT(1X,'N4REAL: NEW ',I3,';')
53  FORMAT(1X,'N4: NEW ',I3,';')


    WRITE(3,54)PPR4
54  FORMAT(1X,'PPR4: NEW ',I3,';')
    WRITE(3,55)LAYER
55  FORMAT(1X,'LAYER: NEW ',I3,';')
*************************************************************************
C   DECLARATION OF DI/DO POINTS
*************************************************************************
    WRITE(3,56)
56  FORMAT(1X,'OPER_ATTNHORN1: NEW 10;')
    WRITE(3,57)
57  FORMAT(1X,'OFF:NEW 0;',/,'OPER_RETRY: NEW 1;',/,'ON:NEW 1;',/
   *'OPER_ATTNHORN: NEW 11;',/,'PORT: NEW 5;')

*************************************************************************
C   WRITING GLOBAL VARIABLES INTO AML FILE
*************************************************************************
```

```
      WRITE(3,58)
58    FORMAT(1X,'PITT: STATIC COUNTER;',/,'TURN :STATIC COUNTER;')
      WRITE(3,59)
59    FORMAT(1X,'SAMPLE1: STATIC PALLET(LL1,LR1,UR1,PPR1,N1);')
      WRITE(3,60)
60    FORMAT(1X,'SAMPLE2: STATIC PALLET(LL2,LR2,UR2,PPR2,N2);')
      WRITE(3,61)
61    FORMAT(1X,'SAMPLE3: STATIC PALLET(LL3,LR3,UR3,PPR3,N3);')
      WRITE(3,62)
62    FORMAT(1X,'SAMPLE4: STATIC PALLET(LL4,LR4,UR4,PPR4,N4);')
      WRITE(3,63)INTERX,INTERY,INTERZ,INTERR,SEMIX,SEMIY,
     *SEMIZ,SEMIR,MATE,CARLX,CARLY,CARLZ,CARLR
63    FORMAT(1X,'INTER:NEW PT(',F7.2,',',F7.2,',',F7.2,',',F7.2,');',/
     *'SEMI:NEW PT(',F7.2,',',F7.2,',',F7.2,',',F7.2,');',/
     *'RESTART:NEW 5;',/,'MATE: NEW ',F7.2,';',/,'ZYLINDER1: NEW 1;',/
     *'ZYLINDER2: NEW 5;',/,'STEP: NEW 16;',/,'HOME1: NEW 9;',/
     *'CAROUSSEL: NEW PT(',F7.2,',',F7.2,',',F7.2,',',F7.2,');',/
     *'PALLET_CENTER: NEW PT(0,0,0,0);',/
     *'DUNN_PICKUP: NEW PT(0,0,0,0);')
      WRITE(3,64)PICKZ
64    FORMAT(1X,'PICKZ: NEW ',F7.2,';')
      WRITE(3,65)PICKX,PICKY
65    FORMAT(1X,'PICKY: NEW PT(',F7.2,',',F7.2,',0,0 );')
*******************************************************************************
C     HEIGHT OF DUNNAGE PILE AFTER EACH LAYER
*******************************************************************************
      DO 67 I=1,LAYER
      DUZ(I)=PT(I)+THICK
      WRITE(3,66)I,DUZ(I)
66    FORMAT(1X,'DUZ',I1,':NEW',F7.2,';')
67    CONTINUE
*******************************************************************************
C     START OF THE MAIN SUBROUTINE
*******************************************************************************
      WRITE(3,68)
68    FORMAT(1X,'MAINPROG:SUBR;')
*******************************************************************************
C     SET_HOME SUBROUTINE TURNS THE CROUSSEL TO KNOWN POSITION
*******************************************************************************
      WRITE(3,69)
69    FORMAT(1X,'SET_HOME:SUBR;')
      WRITE(3,70)
70    FORMAT(1X,'LOOP:WRITEO(STEP,OFF);DELAY(0.1);WRITEO(STEP,ON);',/
     *'DELAY(0.1);TESTI(HOME1,ON,DONE);',/
     *'BRANCH(LOOP);',/,'DONE:BREAKPOINT;',/,'END;')
*******************************************************************************
C     ROTATE SUBROUTINE ROTATES THE CAROUSSEL TO THE REQUESTED DEGREE
*******************************************************************************
      WRITE(3,71)
71    FORMAT(1X,'ROTATE:SUBR(DEGREE);')
      WRITE(3,72)
```

```
72  FORMAT(1X,'SETC(TURN,1);LOOP:WRITEO(STEP,OFF);DELAY(0.1);',/
   *'WRITEO(STEP,ON);DELAY(0.1);',/
   *'TESTC(TURN,DEGREE,DONE);',/,'INCR(TURN);BRANCH(LOOP);',/
   *'DONE:BREAKPOINT;',/,'END;')
    IF(WEIGHT.EQ.1)THEN
*******************************************************************************
C   IF SHIPPER WEIGHT IS IN THE RANGE OF 0 - 5 LB, THE ROBOT WILL
C   PICK UP THE SMALL VACUUM GRIPPER
*******************************************************************************
    WRITE(3,73)
73  FORMAT(1X,'INTERCHANGE_BEGIN_REG:SUBR;')
    WRITE(3,74)
74  FORMAT(1X,'PMOVE(INTER);SET_HOME;PAYLOAD(11);ZONE(1);',/
   *'ZMOVE(MATE);WRITEO(ZYLINDER1,ON);DELAY(2);PMOVE(SEMI);',/
   *'WRITEO(15,ON);ZONE(0);PAYLOAD(0);',/
   *'ZMOVE(0);WRITEO(15,ON);END;')
    ELSE
*******************************************************************************
C   IF SHIPPER WEIGHT IS IN THE RANGE OF 5 - 10 LB, THE ROBOT WILL
C   PICK UP THE BIG VACUUM GRIPPER
*******************************************************************************
    WRITE(3,75)
75  FORMAT(1X,'INTERCHANGE_BEGIN_HEAVY:SUBR;')
    WRITE(3,76)
76  FORMAT(1X,'PMOVE(INTER);PAYLOAD(11);SET_HOME;ROTATE(25);',/
   *'ZONE(1);ZMOVE(MATE);WRITEO(ZYLINDER1,ON);ZONE(0);',/
   *'DELAY(2);PMOVE(SEMI);LINEAR(0);',/,'WRITEO(15,ON);',/
   *'PAYLOAD(0);ZMOVE(0);WRITEO(15,ON);',/,'END;')
    ENDIF
    IF(DUNYES.EQ.1.AND.WEIGHT.EQ.1)THEN
*******************************************************************************
C   DUNN_GRIPPER_ROTATE SUBROUTINE ROTATES THE CAROUSSEL TO ENABLE
C   THE ROBOT TO PICK UP THE DUNNAGE GRIPPER
*******************************************************************************
    WRITE(3,77)
77  FORMAT(1X,'DUNN_GRIPPER_ROTATE:SUBR(PLACE5);')
    WRITE(3,78)
78  FORMAT(1X,'PMOVE(SEMI);LINEAR(1);SET_HOME;PMOVE(CAROUSSEL);',/
   *'WRITEO(ZYLINDER1,OFF);DELAY(2);WRITEO(ZYLINDER2,ON);',/
   *'DELAY(4);WRITEO(ZYLINDER2,OFF);DELAY(5);ZMOVE(0);',/
   *'ROTATE(100);DELAY(2);ZMOVE(MATE);WRITEO(ZYLINDER1,ON);',/
   *'DELAY(2);PMOVE(SEMI);LINEAR(0);PMOVE(DUNN_PICKUP);',/
   *'GRASP;DELAY(1);PMOVE(PALLET_CENTER);GUARDI(8,ON);',/
   *'ZMOVE(PLACE5);NOGUARD;RELEASE;DELAY(1);ZMOVE(0);',/
   *'PMOVE(SEMI);LINEAR(1);SET_HOME;ROTATE(50);PMOVE(CAROUSSEL);',/
   *'WRITEO(ZYLINDER1,OFF);DELAY(2);WRITEO(ZYLINDER2,ON);',/
   *'DELAY(4);WRITEO(ZYLINDER2,OFF);DELAY(5);ZMOVE(0);',/
   *'SET_HOME;DELAY(2);ZMOVE(MATE);WRITEO(ZYLINDER1,ON);',/
   *'DELAY(2);PMOVE(SEMI);LINEAR(0);',/,'END;')
    ENDIF
```

```
      IF(DUNYES.EQ.1.AND.WEIGHT.NE.1)THEN
      WRITE(3,79)
79    FORMAT(1X,'DUNN_GRIPPER_ROTATE:SUBR(PLACE5);')
      WRITE(3,80)
80    FORMAT(1X,'PMOVE(SEMI);LINEAR(1);SET_HOME;',/
     *'ROTATE(25);PMOVE(CAROUSSEL);',/
     *'WRITEO(ZYLINDER1,OFF);DELAY(2);WRITEO(ZYLINDER2,ON);',/
     *'DELAY(4);WRITEO(ZYLINDER2,OFF);DELAY(5);ZMOVE(0);',/
     *'ROTATE(25);DELAY(2);ZMOVE(MATE);WRITEO(ZYLINDER1,ON);',/
     *'DELAY(2);PMOVE(SEMI);LINEAR(0);PMOVE(DUNN_PICKUP);',/
     *'GRASP;DELAY(1);PMOVE(PALLET_CENTER);GUARDI(8,ON);',/
     *'ZMOVE(PLACE5);NOGUARD;RELEASE;DELAY(1);ZMOVE(0);',/
     *'PMOVE(SEMI);LINEAR(1);SET_HOME;ROTATE(50);PMOVE(CAROUSSEL);',/
     *'WRITEO(ZYLINDER1,OFF);DELAY(2);WRITEO(ZYLINDER2,ON);',/
     *'DELAY(4);WRITEO(ZYLINDER2,OFF);DELAY(5);ZMOVE(0);',/
     *'ROTATE(150);DELAY(2);ZMOVE(MATE);WRITEO(ZYLINDER1,ON);',/
     *'DELAY(2);PMOVE(SEMI);LINEAR(0);',/,'END;')
      ENDIF
*************************************************************************
C     WAIT_PART SUBROUTINE SIGNALS THE CONTROLLER WHEN A PART IS
C     PRESENT AT THE PICK UP STATION, IF A PART DOES NOT ARRIVE
C     AFTER 15 SEC., THE OPERATER WILL BE WARNED
*************************************************************************
      WRITE(3,81)
81    FORMAT(1X,'WAIT_PART:SUBR;',/,'WAITI(PORT,ON,15,TROUBLE);',/
     *'BRANCH(DONE);',/,'TROUBLE:WRITEO(OPER_ATTNHORN,ON);',/
     *'WAITI(OPER_RETRY,OFF,0);WAITI(OPER_RETRY,ON,0);',/
     *'WAITI(OPER_RETRY,OFF,0);WRITEO(OPER_ATTNHORN,OFF);',/
     *'DONE:BREAKPOINT;',/,'END;')
*************************************************************************
C     NEW_PALLET SUBROUTINE WILL WARN THE OPERATER THAT THE CURRENT
C     PALLET IS STACKED TO CAPACITY AND GIVES HIM/HER 20 SEC. TO
C     REPLACE THE CURRENT PALLET WITH AN EMPTY ONE. IF PALLET IS
C     NOT REPLACED, THE ROBOT WILL PARK THE GRIPPER AND WAITS TO
C     BE RESTARTED.
*************************************************************************
      IF(WEIGHT.EQ.1)THEN
      WRITE(3,82)
82    FORMAT(1X,'NEW_PALLET:SUBR;',/,'WRITEO(OPER_ATTNHORN1,ON);',/
     *'WAITI(OPER_RETRY,OFF,5);WAITI(OPER_RETRY,ON,10,LOOP_PARK);',/
     *'WAITI(OPER_RETRY,OFF,10);',/,'WRITEO(OPER_ATTNHORN1,OFF);',/
     *'BRANCH(DONE);',/,'LOOP_PARK:ZMOVE(0);PMOVE(SEMI);LINEAR(1);',/
     *'WRITEO(OPER_ATTNHORN1,OFF);WRITEO(15,OFF);SET_HOME;',/
     *'PMOVE(CAROUSSEL);WRITEO(ZYLINDER1,OFF);DELAY(3);',/
     *'WRITEO(ZYLINDER2,ON);DELAY(3);WRITEO(ZYLINDER2,OFF);',/
     *'DELAY(5);LINEAR(1);ZMOVE(-150);LINEAR(0);ZMOVE(0);',/
     *'DONE:BREAKPOINT;WRITEO(OPER_ATTNHORN1,OFF);',/
     *'PMOVE(PT(650,0,0,0));',/,'END;')
      ELSE
      WRITE(3,83)
83    FORMAT(1X,'NEW_PALLET:SUBR;',/,'WRITEO(OPER_ATTNHORN1,ON);',/
```

```
   *'WAITI(OPER_RETRY,OFF,5);WAITI(OPER_RETRY,ON,10,LOOP_PARK);',/
   *'WAITI(OPER_RETRY,OFF,10);',/,'WRITEO(OPER_ATTNHORN1,OFF);',/
   *'BRANCH(DONE);',/,'LOOP_PARK:ZMOVE(0);PMOVE(SEMI);LINEAR(1);',/
   *'WRITEO(15,OFF);WRITEO(OPER_ATTNHORN1,OFF);SET_HOME;ROTATE(25);',/
   *'PMOVE(CAROUSSEL);WRITEO(ZYLINDER1,OFF);DELAY(3);',/
   *'WRITEO(ZYLINDER2,ON);DELAY(3);WRITEO(ZYLINDER2,OFF);',/
   *'DELAY(5);LINEAR(1);ZMOVE(-150);LINEAR(0);ZMOVE(0);',/
   *'DONE:BREAKPOINT;WRITEO(OPER_ATTNHORN1,OFF);',/
   *'PMOVE(PT(650,0,0,0));',/,'END;')
     ENDIF
*************************************************************************
C   PICKUP SUBROUTINE STACKS THE FIRST PART OF EVERY ODD LAYER
*************************************************************************
    WRITE(3,84)
84   FORMAT(1X,'PICKUP:SUBR(PLACE1);')
    WRITE(3,85)
85  FORMAT(1X,'SET: SETPART(SAMPLE1,1);')
    WRITE(3,86)
86  FORMAT(1X,'LOOP:WAIT_PART;PMOVE(PICKY);ZMOVE(PICKZ);')
    WRITE(3,87)
87  FORMAT(1X,'GRASP;DELAY(1);ZMOVE(0);')
    WRITE(3,88)
88  FORMAT(1X,'GETPART(SAMPLE1);GUARDI(8,1);ZMOVE(PLACE1);',/
   *'NOGUARD;RELEASE;DELAY(1);')
    WRITE(3,89)
89  FORMAT(1X,'ZMOVE(0);TESTP(SAMPLE1,N1REAL,DONE);')
    WRITE(3,90)
90  FORMAT(1X,'NEXTPART(SAMPLE1);')
    WRITE(3,91)
91  FORMAT(1X,'BRANCH(LOOP);')
    WRITE(3,92 )
92  FORMAT(1X,'DONE:BREAKPOINT;')
    WRITE(3,93)
93  FORMAT(1X,'END;')
*************************************************************************
C   OLDPR SUBROUTINE STACKS THE SECOND PART OF EVERY ODD LAYER
*************************************************************************
    WRITE(3,94)
94  FORMAT(1X,'OLDPR:SUBR(PLACE2);')
    WRITE(3,95)
95  FORMAT(1X,'SET: SETPART(SAMPLE2,1);')
    WRITE(3,96)
96  FORMAT(1X,'LOOP:WAIT_PART;PMOVE(PICKY);ZMOVE(PICKZ);')
    WRITE(3,97)
97  FORMAT(1X,'GRASP;DELAY(1);ZMOVE(0);')
    WRITE(3,98)
98  FORMAT(1X,'GETPART(SAMPLE2);GUARDI(8,1);ZMOVE(PLACE2);',/
   *'NOGUARD;RELEASE;DELAY(1);')
    WRITE(3,99)
99  FORMAT(1X,'ZMOVE(0);TESTP(SAMPLE2,N2REAL,DONE);')
    WRITE(3,100)
```

```
100  FORMAT(1X,'NEXTPART(SAMPLE2);')
     WRITE(3,101)
101  FORMAT(1X,'BRANCH(LOOP);')
     WRITE(3,102)
102  FORMAT(1X,'DONE:BREAKPOINT;')
     WRITE(3,103)
103  FORMAT(1X,'END;')
*************************************************************************
C    NEWPR SUBROUTINE STACKS THE FIRST PART OF EVERY EVEN LAYER
*************************************************************************
     WRITE(3,104)
104  FORMAT(1X,'NEWPR:SUBR(PLACE3);')
     WRITE(3,105)
105  FORMAT(1X,'SET: SETPART(SAMPLE3,1);')
     WRITE(3,106)
106  FORMAT(1X,'LOOP:WAIT_PART;PMOVE(PICKY);ZMOVE(PICKZ);')
     WRITE(3,107)
107  FORMAT(1X,'GRASP;DELAY(1);ZMOVE(0);')
     WRITE(3,108)
108  FORMAT(1X,'GETPART(SAMPLE3);GUARDI(8,1);ZMOVE(PLACE3);',/
    *'NOGUARD;RELEASE;DELAY(1);')
     WRITE(3,109)
109  FORMAT(1X,'ZMOVE(0);TESTP(SAMPLE3,N3REAL,DONE);')
     WRITE(3,110)
110  FORMAT(1X,'NEXTPART(SAMPLE3);')
     WRITE(3,111)
111  FORMAT(1X,'BRANCH(LOOP);')
     WRITE(3,112)
112  FORMAT(1X,'DONE:BREAKPOINT;')
     WRITE(3,113)
113  FORMAT(1X,'END;')
*************************************************************************
C    LAST PROGRAM STACKS THE SECOND PART OF EVERY EVEN LAYER
*************************************************************************
     WRITE(3,114)
114  FORMAT(1X,'LAST:SUBR(PLACE4);')
     WRITE(3,115)
115  FORMAT(1X,'SET: SETPART(SAMPLE4,1);')
     WRITE(3,116)
116  FORMAT(1X,'LOOP:WAIT_PART;PMOVE(PICKY);ZMOVE(PICKZ);')
     WRITE(3,117)
117  FORMAT(1X,'GRASP;DELAY(1);ZMOVE(0);')
     WRITE(3,118)
118  FORMAT(1X,'GETPART(SAMPLE4);GUARDI(8,1);ZMOVE(PLACE4);',/
     *'NOGUARD;RELEASE;DELAY(1);')
     WRITE(3,119)
119  FORMAT(1X,'ZMOVE(0);TESTP(SAMPLE4,N4REAL,DONE);')
     WRITE(3,120)
120  FORMAT(1X,'NEXTPART(SAMPLE4);')
     WRITE(3,121)
121  FORMAT(1X,'BRANCH(LOOP);')
```

```
      WRITE(3,122)
122    FORMAT(1X,'DONE:BREAKPOINT;')
      WRITE(3,123)
      123FORMAT(1X,'END;')
      I=1
*************************************************************************
C     CALLING THE DIFFERENT SUBROUTINES FOR ALL DIFFERENT CASES
*************************************************************************
      IF(DUNYES.EQ.1)THEN
      IF(WEIGHT.EQ.1)THEN
      WRITE(3,124)
124    FORMAT(1X,'INTERCHANGE_BEGIN_REG;')
      ELSE
      WRITE(3,125)
125    FORMAT(1X,'INTERCHANGE_BEGIN_HEAVY;')
      ENDIF
      WW=1
      WRITE(3,126)
126    FORMAT(1X,'OVER:SETC(PITT,0);')
127    CONTINUE
      IF(I.LE.4)THEN
      WRITE(3,128)I
128    FORMAT(1X,'PICKUP(Z',I1,');')
      WRITE(3,129)I
129    FORMAT(1X,'OLDPR(Z',I1,');')
      WRITE(3,130)
130    FORMAT(1X,'INCR(PITT);')
      WRITE(3,131)WW,WW+1,WW
131    FORMAT(1X,'TESTC(PITT,LAYER,LOOP',I1,');',/
     *'BRANCH(LOOP',I1,');',/,'LOOP',I1,':NEW_PALLET;',/
     *'WAITI(RESTART,OFF,0);WAITI(RESTART,ON,0);WAITI(RESTART,OFF,0);',/
     *'BRANCH(OVER);')
      WRITE(3,132)WW+1,I
132    FORMAT(1X,'LOOP',I1,':DUNN_GRIPPER_ROTATE(DUZ',I1,');')
      WW=WW+2
      IF(I.EQ.LAYER)GOTO168
      I=I+1
      WRITE(3,133)I
133    FORMAT(1X,'NEWPR(Z',I1,');')
      WRITE(3,134)I
134    FORMAT(1X,'LAST(Z',I1,');')
      WRITE(3,135)
135    FORMAT(1X,'INCR(PITT);')
      WRITE(3,136)WW,WW+1,WW,WW+1,I
136    FORMAT(1X,'TESTC(PITT,LAYER,LOOP',I1,');',/
     *'BRANCH(LOOP',I1,');',/,'LOOP',I1,':NEW_PALLET;',/
     *'WAITI(RESTART,OFF,0);WAITI(RESTART,ON,0);WAITI(RESTART,OFF,0);',/
     *'BRANCH(OVER);',/,'LOOP',I1,':DUNN_GRIPPER_ROTATE(DUZ',I1,');')
      WW=WW+2
      IF(I.EQ.LAYER)GOTO168
      I=I+1
```

```
      GOTO127
      ELSE
      WW=WW+4
137   WRITE(3,138)I
138   FORMAT(1X,'PICKUP(Z',I1,');')
      WRITE(3,139)I
139   FORMAT(1X,'OLDPR(Z',I1,');')
      WRITE(3,140)WW,WW+1,WW
140   FORMAT(1X,'TESTC(PITT,LAYER,LOOP',I2,');',/
     *'BRANCH(LOOP',I2,');',/,'LOOP',I2,':NEW_PALLET;',/
     *'WAITI(RESTART,OFF,0);WAITI(RESTART,ON,0);WAITI(RESTART,OFF,0);',/
     *'BRANCH(OVER);')
      WRITE(3,141)WW+1,I
141   FORMAT(1X,'LOOP',I2,':DUNN_GRIPPER_ROTATE(DUZ',I1,');')
      WW=WW+2
      IF(I.EQ.LAYER)GOTO168
      I=I+1
      WRITE(3,142)I
142   FORMAT(1X,'NEWPR(Z',I1,');')
      WRITE(3,143)I
143   FORMAT(1X,'LAST(Z',I1,');')
      WRITE(3,144)
144   FORMAT(1X,'INCR(PITT);')
      WRITE(3,145)WW,WW+1,WW,WW+1,I
145   FORMAT(1X,'TESTC(PITT,LAYER,LOOP',I2,');',/
     *'BRANCH(LOOP',I2,');',/,'LOOP',I2,':NEW_PALLET;',/
     *'BRANCH(OVER);',/,'LOOP',I2,':DUNN_GRIPPER_ROTATE(DUZ',I1,');')
      WW=WW+2
      IF(I.EQ.LAYER)GOTO168
      I=I+1
      GOTO137
      ENDIF
      ELSE
      WW=1
      IF(WEIGHT.EQ.1)THEN
      WRITE(3,146)
146   FORMAT(1X,'INTERCHANGE_BEGIN_REG;')
      ELSE
      WRITE(3,147)
147   FORMAT(1X,'INTERCHANGE_BEGIN_HEAVY;')
      ENDIF
      WRITE(3,148)
148   FORMAT(1X,'OVER:SETC(PITT,0);')
      149CONTINUE
      IF(I.LE.4)THEN
      WRITE(3,150)I
150   FORMAT(1X,'PICKUP(Z',I1,');')
      WRITE(3,151)I
151   FORMAT(1X,'OLDPR(Z',I1,');',/,'INCR(PITT);')
      WRITE(3,152)WW,WW+1,WW
152   FORMAT(1X,'TESTC(PITT,LAYER,LOOP',I1,');',/
```

```
     *'BRANCH(LOOP',,I1,');',/,'LOOP',I1,':NEW_PALLET;',/
     *'WAITI(RESTART,OFF,0);WAITI(RESTART,ON,0);WAITI(RESTART,OFF,0);',/
     *'BRANCH(OVER);')
     WRITE(3,153)WW+1
153   FORMAT(1X,'LOOP',I1,':DELAY(1);')
     IF(I.EQ.LAYER)GOTO167
     I=I+1
     WW=WW+2
     WRITE(3,154)I
154   FORMAT(1X,'NEWPR(Z',I1,');')
     WRITE(3,156)I
156   FORMAT(1X,'LAST(Z',I1,');')
     WRITE(3,157)
157   FORMAT(1X,'INCR(PITT);')
     WRITE(3,158)WW,WW+1,WW
158   FORMAT(1X,'TESTC(PITT,LAYER,LOOP',I1,');',/
     *'BRANCH(LOOP',,I1,');',/,'LOOP',I1,':NEW_PALLET;',/
     *'WAITI(RESTART,OFF,0);WAITI(RESTART,ON,0);WAITI(RESTART,OFF,0);',/
     *'BRANCH(OVER);')
     WRITE(3,159)WW+1
159   FORMAT(1X,'LOOP',I1,':DELAY(1);')
     IF(I.EQ.LAYER)GOTO168
     WW=WW+2
     I=I+1
     GOTO149
     ELSE
     WW=WW+4
     WRITE(3,160)WW,WW+1,WW
160   FORMAT(1X,'TESTC(PITT,LAYER,LOOP',I2,');',/
     *'BRANCH(LOOP',,I2,');',/,'LOOP',I2,':NEW_PALLET;',/
     *'WAITI(RESTART,OFF,0);WAITI(RESTART,ON,0);WAITI(RESTART,OFF,0);',/
     *'BRANCH(OVER);')
     WRITE(3,161)WW+1
161   FORMAT(1X,'LOOP',I2,':DELAY(1);')
     IF(I.EQ.LAYER)GOTO167
     I=I+1
     WW=WW+2
     WRITE(3,162)I
162   FORMAT(1X,'NEWPR(Z',I1,');')
     WRITE(3,163)I
163   FORMAT(1X,'LAST(Z',I1,');')

     WRITE(3,164)
164   FORMAT(1X,'INCR(PITT);')
     WRITE(3,165)WW,WW+1,WW
165   FORMAT(1X,'TESTC(PITT,LAYER,LOOP',I2,');',/
     *'BRANCH(LOOP',,I2,');',/,'LOOP',I2,':NEW_PALLET;',/
     *'WAITI(RESTART,OFF,0);WAITI(RESTART,ON,0);WAITI(RESTART,OFF,0);',/
     *'BRANCH(OVER);')
     WRITE(3,166)WW+1
166   FORMAT(1X,'LOOP',I2,':DELAY(1);')
```

```
      IF(I.EQ.LAYER)GOTO168
      WW=WW+2
      I=I+1
      GOTO149
      ENDIF
      ENDIF
167   CONTINUE
168   WRITE(3,169)
169   FORMAT(1X,'END;')
170   STOP
      END
*****************************************************************************
C     SUBROUTINE TO INTERACTIVELY COMMUNICATE WITH THE USER
*****************************************************************************
      SUBROUTINE PRINT (ROW,COL,STRING,LENGT)
      INTEGER PAGE, ROW, COL, LENGT, CHAR
      CHARACTER STRING(LENGT)
      CALL CURPAG(PAGE)
      CALL LOCATE(PAGE,ROW,COL)
      DO 171 I=1,LENGT
      CHAR=ICHAR(STRING(I))
      CALL WRTTY(CHAR)
171   CONTINUE
      RETURN
      END
```

APPENDIX B

COMBINED HEURISTIC

```
C    PROGRAM TO CALCULATE A PALLET PATTERN
     INTEGER BLACK,BLUE,GREEN,CYAN,RED,MAGENTA,YELLOW
     INTEGER WHITE,BBLACK,BBLUE,BGREEN,BCYAN,BRED
     INTEGER BMAGENTA,BYELLOW,BWHITE,BLINK,HIGHINT
     INTEGER X,J,B,A1,C1,C2,Y,Z1,P,A,Z,X6
     INTEGER K,A2,A3,A4,A5,M,I,N,A6,A7,A8,A9,E
     INTEGER NN,IIJ,KK,JK,IJ,III,JJJ,LENGT,ATTRIB,PPR1,PPR2,PPR3
     INTEGER PPR4,N1,N2,N3,N4,WEIGHT,N1R,N2R,N3R,N4R,WW
     INTEGER IL,TOTALN,OPT,NBOX,AX1,AX2,AX3,AX4,AY1,AY2,AY3,AY4
     INTEGER BX1,BX2,BX3,BX4,BY1,BY2,BY3,BY4,GES1,GES2
     REAL LENGTH, WIDTH, HEIGHT, UTIL, L, H, W,X7,XK,XL,LEFTX,LEFTY
     REAL RIGHTX,RIGHTY,UPRX,UPRY,PICKX,PICKY,PICKZ,PICKR,HFRAME
     REAL XBOX,XBOX1,YBOX,YBOX1,P1,P2,LO,WO,HO,XBOX2,XBOX3
     REAL ZMOVE,ZPICK,LLX1,LLX2,LLX3,LLX4,LLY1,LLY2,LLY3,LLY4
     REAL LRX1,LRX2,LRX3,LRX4,LRY1,LRY2,LRY3,LRY4,URX1,URX2,URX3,URX4
     REAL PICKX1,PICKY1,PT(100),X11,X22,X33,X44,DUZ(20),INTERX,INTERY
     REAL INTERZ,INTERR,SEMIX,SEMIY,SEMIZ,SEMIR,MATE,CARLX
     REAL CARLY,CARLZ,CARLR,X1,Y1
     DOUBLE PRECISION M1(20,20)
     CHARACTER*70 STR1,STR6
     CHARACTER STR2(70),STR3(70),STR7(70),STR8(70)
     EQUIVALENCE (STR1,STR2(1))
     EQUIVALENCE (STR6,STR7(1))
     DATA BLACK,BLUE,GREEN,CYAN,RED,MAGENTA,YELLOW /0,1,2,3,4,5,6/
     DATA WHITE,BBLACK,BBLUE,BGREEN,BCYAN,BRED /7,0,16,32,48,64/
     DATA BMAGENTA,BYELLOW,BWHITE,BLINK,HINGHINT /80,96,112,128,8/
     L=250.00
     W=210.00
     LEFTX=-244.
     LEFTY=300.00
     RIGHTX=0.0
     RIGHTY=300.00
     UPRX=0.0
     UPRY=503.20
     HFRAME=20.0
     PICKX=400.00
     PICKY=400.00
     PICKZ=-162.00
     PICKR=0.0
     INTERX=-401.0
     INTERY=-318.3
     INTERZ=0.0
     INTERR=54.0
     SEMIX=-401.0
     SEMIY=-200.0
     SEMIZ=-212.0
     SEMIR=54.0
     MATE=-214.6
     CARLX=-401.0
     CARLY=-318.3
     CARLZ=-212.0
```

```
      CARLR=54.0
      X=0
      E=0
      J=0
      XK=0.0
      XL=0.0
      X1=0
      ATTRIB=WHITE + BBLUE
      CALL CLS(ATTRIB)
      CALL PRINT(10,15,'THIS PROGRAM CALCULATES A PALLET PATTERN',40)
      GOTO3
*************************************************************************
C     QUERY USER FOR INPUT DATA
*************************************************************************
2     CALL PRINT(10,19,'PLEASE MAKE SURE THAT LENGTH GREATER WIDTH',42)
3     CALL PRINT(13,21,'TYPE 1 IF YOU WANT THE INPUT IN INCHES',38)
*************************************************************************
C     DETERMINE WHETHER THE USER PREFERS TO WORK IN INCHES OR MM
*************************************************************************
       CALL PRINT(15,22,'TYPE 0 IF YOU WANT THE INPUT IN MM',34)
       CALL PRINT(17,30,'ENTER OPTION  ==>',17)
      CALL INKEY(INCH,MM)
      IF(INCH.EQ.49)THEN
      CALL CLS(ATTRIB)
      CALL PRINT(10,22,'PLEASE GIVE WIDTH OF SHIPPER IN INCH',36)
      CALL PRINT(12,30,'ENTER OPTION  ==>',17)
      READ (*,*)WIDTH
      CALL CLS(ATTRIB)
      CALL PRINT(10,21,'PLEASE GIVE LENGTH OF SHIPPER IN INCH',37)
      CALL PRINT(12,30,'ENTER OPTION  ==>',17)
      READ (*,*)LENGTH
      CALL CLS(ATTRIB)
      CALL PRINT(10,21,'PLEASE GIVE HEIGTH OF SHIPPER IN INCH',37)
      CALL PRINT(12,30,'ENTER OPTION  ==>',17)
      READ (*,*)HEIGHT
      CALL CLS(ATTRIB)
      CALL PRINT(10,20,'PLEASE GIVE MAX. HEIGHT OF PALLET IN INCH',41)
      CALL PRINT(12,30,'ENTER OPTION  ==>',17)
      READ(*,*)H
      CALL CLS(ATTRIB)
      CALL PRINT(10,20,'TYPE 1 IF BOX WEIGHT IS IN THE RANGE OF',39)
      CALL PRINT(11,30,'0 - 5 lb.',9)
      CALL PRINT(15,20,'TYPE 0 IF BOX WEIGHT IS IN THE RANGE OF',39)
      CALL PRINT(16,30,'5 - 10 lb.',10)
      CALL PRINT(18,30,'ENTER OPTION  ==>',17)
      READ(*,*)WEIGHT
      CALL CLS(ATTRIB)
      CALL PRINT(10,20,'TYPE 1 IF THE PALLET SHALL BE STACKED',37)
      CALL PRINT(12,25,'WITH DUNNAGE, ELSE TYPE 0',25)
      CALL PRINT(14,30,'ENTER OPTION  ==>',17)
      READ (*,*)DUNYES
```

```
      IF(DUNYES.EQ.1)THEN
      CALL CLS(ATTRIB)
      CALL PRINT(10,20,'PLEASE GIVE THICKNESS OF DUNNAGE IN INCH',40)
      CALL PRINT(12,30,'ENTER OPTION  ==>',17)
      READ(*,*)THICK
      ENDIF
*************************************************************************
C     TRANSFORMING INCHES INTO MM
*************************************************************************
      WIDTH=WIDTH*25.4
      LENGTH=LENGTH*25.4
      HEIGHT=HEIGHT*25.4
      H=H*25.4
      THICK=THICK*25.4
      ELSE
      CALL CLS(ATTRIB)
      CALL PRINT(10,18,'PLEASE GIVE WIDTH OF SHIPPER IN MM',34)
      CALL PRINT(12,30,'ENTER OPTION  ==>',17)
      READ (*,*)WIDTH
      CALL CLS(ATTRIB)
      CALL PRINT(10,19,'PLEASE GIVE LENGTH OF SHIPPER IN MM',35)
      CALL PRINT(12,30,'ENTER OPTION  ==>',17)
      READ(*,*)LENGTH
      CALL CLS(ATTRIB)
      CALL PRINT(10,19,'PLEASE GIVE HEIGTH OF SHIPPER IN MM',35)
      CALL PRINT(12,30,'ENTER OPTION  ==>',17)
      READ (*,*)HEIGHT
      CALL CLS(ATTRIB)
      CALL PRINT(10,20,'PLEASE GIVE MAX. HEIGHT OF PALLET IN MM',39)
      CALL PRINT(12,30,'ENTER OPTION  ==>',17)
      READ(*,*)H
      CALL CLS(ATTRIB)
      CALL PRINT(10,20,'TYPE 1 IF BOX WEIGHT IS IN THE RANGE OF',39)
      CALL PRINT(11,30,'0 - 5 lb.',9)
      CALL PRINT(15,20,'TYPE 0 IF BOX WEIGHT IS IN THE RANGE OF',39)
      CALL PRINT(16,30,'5 - 10 lb.',10)
      CALL PRINT(18,30,'ENTER OPTION  ==>',17)
      READ(*,*)WEIGHT
      CALL CLS(ATTRIB)
      CALL PRINT(10,20,'TYPE 1 IF THE PALLET SHALL BE STACKED',37)
      CALL PRINT(12,25,'WITH DUNNAGE, ELSE TYPE 0',25)
      CALL PRINT(14,30,'ENTER OPTION  ==>',17)
      READ (*,*)DUNYES
      IF(DUNYES.EQ.1)THEN
      CALL CLS(ATTRIB)
      CALL PRINT(10,20,'PLEASE GIVE THICKNESS OF DUNNAGE IN MM',38)
      CALL PRINT(12,30,'ENTER OPTION  ==>',17)
      READ(*,*)THICK
      ENDIF
      ENDIF
```

```
      IF(WIDTH.GT.LENGTH)GOTO 2
      IF(W.GT.L)GOTO 2
*************************************************************************
C     HEURIC ALOGRITHM BEGINNS
*************************************************************************
      TOTALN=INT(W/WIDTH)
      OPT=0
      IL=1
4     I=1
      DO 6 I=1,TOTALN
      X1=REAL(WIDTH*I)
      IF(X1.GT.W)THEN
      IL=IL+1
      GOTO 4
      ENDIF
      Y1=REAL(LENGTH*IL)
      IF(Y1.GT.L)GOTO 7
      IF((W-X1).LT.LENGTH)THEN
      NBOX=I*IL+INT((W-Y1)/(WIDTH))*INT(X1/(LENGTH))+
     *INT((W-X1)/(WIDTH))*INT(L-Y1)/(LENGTH)
      IF(NBOX.GT.OPT)THEN
      OPT=NBOX
      AX1=I
      AX2=0
      AY2=0
      AY1=INT(Y1/LENGTH)
      AX3=INT((W-X1)/WIDTH)
      AX4=INT(X1/LENGTH)
      AY3=INT((L-Y1)/LENGTH)
      AY4=INT((L-Y1)/WIDTH)
      ENDIF
      IF((W-X1).LT.WIDTH)THEN
      NBOX=I*IL+INT((W-Y1)/(WIDTH))*INT(X1/LENGTH)
      IF(NBOX.GT.OPT)THEN
      OPT=NBOX
      AX1=I
      AX2=0
      AY1=INT(Y1/LENGTH)
      AY2=0
      AX3=0
      AX4=INT(X1/LENGTH)
      AY3=0
      AY4=INT((L-Y1)/WIDTH)
      ENDIF
      ENDIF
      GOTO 6
      ENDIF
      NBOX=I*IL+INT((W-X1)/(LENGTH))*INT(Y1/WIDTH)+
     *INT((W-X1)/(WIDTH))*INT((L-Y1)/(LENGTH))+
     *INT(X1/LENGTH)*INT(L-Y1)/(WIDTH)
      IF(NBOX.GT.OPT)THEN
```

```
      OPT=NBOX
      AX1=I
      AX2=INT((W-X1)/LENGTH)
      AY1=INT(Y1/LENGTH)
      AY2=INT(Y1/WIDTH)
      AX3=INT((W-X1)/WIDTH)
      AX4=INT(X1/LENGTH)
      AY3=INT((L-Y1)/LENGTH)
      AY4=INT((L-Y1)/WIDTH)
      ENDIF
6     CONTINUE
7     CONTINUE
      IF(AX1.EQ.0)AY1=0
      IF(AX2.EQ.0)AY2=0
      IF(AX3.EQ.0)AY3=0
      IF(AX4.EQ.0)AY4=0
      IF(AY1.EQ.0)AX1=0
      IF(AY2.EQ.0)AX2=0
      IF(AY3.EQ.0)AX3=0
      IF(AY4.EQ.0)AX4=0
      GES1=AX1*AY1+AX2*AY2+AX3*AY3+AX4*AY4
      TOTALN=INT(L/WIDTH)
      OPT=0
      IL=1
8     I=1
      DO 9 I=1,TOTALN
      X1=REAL(WIDTH*I)
      IF(X1.GT.L)THEN
      IL=IL+1
      GOTO 8
      ENDIF
      Y1=REAL(LENGTH*IL)
      IF(Y1.GT.W)GOTO 10
      IF((L-X1).LT.LENGTH)THEN
      NBOX=I*IL+INT((L-Y1)/WIDTH)*INT(X1/LENGTH)+
     *INT((L-X1)/(WIDTH))*INT((W-Y1)/(LENGTH))
      IF(NBOX.GT.OPT)THEN
      OPT=NBOX
      BX1=I
      BX2=0
      BY2=0
      BY1=INT(Y1/LENGTH)
      BX3=INT((L-X1)/WIDTH)
      BX4=INT(X1/LENGTH)
      BY3=INT((W-Y1)/LENGTH)
      BY4=INT((W-Y1)/WIDTH)
      ENDIF
      IF((L-X1).LT.WIDTH)THEN
      NBOX=I*IL+(INT((L-Y1)/(WIDTH))*(INT(X1/LENGTH)))
      IF(NBOX.GT.OPT)THEN
      OPT=NBOX
```

```
      BX1=I
      BX2=0
      BY1=INT(Y1/LENGTH)
      BY2=0
      BX3=0
      BX4=INT(X1/LENGTH)
      BY3=0
      BY4=INT((W-Y1)/WIDTH)
      ENDIF
      ENDIF
      GOTO 9
      ENDIF
      NBOX=I*IL+INT((L-X1)/LENGTH)*INT(Y1/WIDTH)+
     *INT((L-X1)/WIDTH)*INT((W-Y1)/LENGTH)+
     *INT(X1/LENGTH)*INT((W-Y1)/(WIDTH))
      IF(NBOX.GT.OPT)THEN
      OPT=NBOX
      BX1=I
      BX2=INT((L-X1)/LENGTH)
      BY1=INT(Y1/LENGTH)
      BY2=INT(Y1/WIDTH)
      BX3=INT((L-X1)/WIDTH)
      BX4=INT(X1/LENGTH)
      BY3=INT((W-Y1)/LENGTH)
      BY4=INT((W-Y1)/WIDTH)
      ENDIF
9     CONTINUE
10    CONTINUE
      IF(BX1.EQ.0)BY1=0
      IF(BX2.EQ.0)BY2=0
      IF(BX3.EQ.0)BY3=0
      IF(BX4.EQ.0)BY4=0
      IF(BY1.EQ.0)BX1=0
      IF(BY2.EQ.0)BX2=0
      IF(BY3.EQ.0)BX3=0
      IF(BY4.EQ.0)BX4=0
      GES2=BX1*BY1+BX2*BY2+BX3*BY3+BX4*BY4
      LAYER=INT(H/HEIGHT)
*************************************************************************
C     PRINTING THE UTILIZATION, THE # OF
C     SHIPPERS PER LAYER, AND THE TOTAL # OF SHIPPERS ON THE PALLET.
*************************************************************************
      IF(GES2.GT.GES1)THEN
      X6=GES2*LAYER
      UTIL=REAL(GES2*LENGTH*WIDTH*100/(204.0*244.0))
      CALL CLS(ATTRIB)
      WRITE(*,11)BX1,BY1
11    FORMAT(1X,'X1=',1X,I7,'Y1=',1X,I7)
      WRITE(*,12)BX2,BY2
12    FORMAT(1X,'X2=',1X,I7,'Y2=',1X,I7)
      WRITE(*,13)BX3,BY3
```

```
13  FORMAT(1X,'X3=',1X,I7,'Y3=',1X,I7)
    WRITE(*,14)BX4,BY4
14  FORMAT(1X,'X4=',1X,I7,'Y4=',1X,I7)
    WRITE(*,15)GES2
15  FORMAT(1X,'TOTAL NUMBER OF SHIPPER PER LAYER=',1X,I7)
    WRITE(*,16)X6
16  FORMAT(1X,'TOTAL NUMBER OF SHIPPER ON PALLET=',1X,I7)
    WRITE(*,17)UTIL
17  FORMAT(1X,'PALLET UTILIZATION=',1X,F5.2,1X,'PERCENT')
    ELSE
    X6=GES1*LAYER
    UTIL=REAL(GES1*LENGTH*WIDTH*100/(204.0*244.0))
    CALL CLS(ATTRIB)
    WRITE(*,18)AX1,AY1
18  FORMAT(1X,'X1=',1X,I7,'Y1=',1X,I7)
    WRITE(*,19)AX2,AY2
19  FORMAT(1X,'X2=',1X,I7,'Y2=',1X,I7)
    WRITE(*,20)AX3,AY3
20  FORMAT(1X,'X3=',1X,I7,'Y3=',1X,I7)
    WRITE(*,21)AX4,AY4
21  FORMAT(1X,'X4=',1X,I7,'Y4=',1X,I7)
    WRITE(*,22)GES1
22  FORMAT(1X,'TOTAL NUMBER OF SHIPPER PER LAYER=',1X,I7)
    WRITE(*,23)X6
23  FORMAT(1X,'TOTAL NUMBER OF SHIPPER ON PALLET=',1X,I7)
    WRITE(*,24)UTIL
24  FORMAT(1X,'PALLET UTILIZATION=',1X,F5.2,1X,'PERCENT')
    ENDIF
*************************************************************************
C   DETERMIN THE Z VALUE OF EVERY LAYER ON THE PALLET
*************************************************************************
    ZMOVE=-250+(HFRAME+HEIGHT)
*************************************************************************
C   CREATING AN ARTIFICIAL EXTRA ROW IF INITIAL PALLET CONSISTS OF
C   ONLY ONE ROW
*************************************************************************
    IF(AX1.EQ.1)THEN
    AX11=2
    ELSE
    AX11=AX1
    ENDIF
    IF(AX2.EQ.1)THEN
    AX22=2
    ELSE
    AX22=AX2
    ENDIF
    IF(AX3.EQ.1)THEN
    AX33=2
    ELSE
    AX33=AX3
    ENDIF
```

```
IF(AX4.EQ.1)THEN
AX44=2
ELSE
AX44=AX4
ENDIF
IF(AY1.EQ.1)THEN
AY11=2
ELSE
AY11=AY1
ENDIF
IF(AY2.EQ.1)THEN
AY22=2
ELSE
AY22=AY2
ENDIF
IF(AY3.EQ.1)THEN
AY33=2
ELSE
AY33=AY3
ENDIF
IF(AY4.EQ.1)THEN
AY44=2
ELSE
AY44=AY4
ENDIF
IF(BX1.EQ.1)THEN
BX11=2
ELSE
BX11=BX1
ENDIF
IF(BX2.EQ.1)THEN
BX22=2
ELSE
BX22=BX2
ENDIF
IF(BX3.EQ.1)THEN
BX33=2
ELSE
BX33=BX3
ENDIF
IF(BX4.EQ.1)THEN
BX44=2
ELSE
BX44=BX4
ENDIF
IF(BY1.EQ.1)THEN
BY11=2
ELSE
BY11=BY1
ENDIF
IF(BY2.EQ.1)THEN
```

```
      BY22=2
      ELSE
      BY22=BY2
      ENDIF
      IF(BY3.EQ.1)THEN
      BY33=2
      ELSE
      BY33=BY3
      ENDIF
      IF(BY4.EQ.1)THEN
      BY44=2
      ELSE
      BY44=BY4
      ENDIF
*************************************************************************
C     DETERMINING THE LOWER LEFT, LOWER RIGHT, UPPER RIGHT CORNER
C     SHIPPER CENTER POINTS FOR ALL 4 POSSIBLE PALLET CONFIGURATIONS
*************************************************************************
      IF(GES2.GE.GES1)THEN
      LLX1=180.0-((BX1*WIDTH)-(WIDTH/2))
      LLY1=290.0+LENGTH/2
      LRX1=180-WIDTH/2
      LRY1=LLY1
      URX1=LRX1
      URY1=290.0+((BY1*LENGTH)-LENGTH/2)
      N1=BX11*BY11
      N1R=BX1*BY1
      PPR1=BX1

      IF(BX2.EQ.0)GOTO1000
      LLX2=-64.0+LENGTH/2
      LLY2=290.0+WIDTH/2
      LRX2=LLX2+(BX2-1)*LENGTH
      LRY2=LLY2
      URX2=LRX2
      URY2=290.0+((BY2*WIDTH)-WIDTH/2)
      N2=BX22*BY22
      N2R=BX2*BY2
      PPR2=BX2

1000  IF(BX3.EQ.0)GOTO1001

      LLX3=-64.0+WIDTH/2
      LLY3=500.0-(BY3*LENGTH-LENGTH/2)
      LRX3=LLX3+(BX3-1)*WIDTH
      LRY3=LLY3
      URX3=LRX3
      URY3=500.0-LENGTH/2
      N3=BX33*BY33
      N3R=BX3*BY3
      PPR3=BX3
```

```
1001 IF(BX4.EQ.0)GOTO1002

     LLX4=180.0-((BX4*LENGTH)-(LENGTH/2))
     LLY4=500.0-(BY4*WIDTH-WIDTH/2)
     LRX4=180-LENGTH/2
     LRY4=LLY4
     URX4=LRX4
     URY4=500.0-WIDTH/2
     N4=BX44*BY44
     N4R=BX4*BY4
     PPR4=BX4

1002 ELSE

     IF(AX4.EQ.0)GOTO1003

     LLX1=180.0-((AX4*WIDTH)-(WIDTH/2))
     LLY1=290.0+LENGTH/2
     LRX1=180-WIDTH/2
     LRY1=LLY1
     URX1=LRX1
     URY1=290.0+((AY4*LENGTH)-LENGTH/2)
     N1=AX44*AY44
     N1R=AX4*AY4
     PPR1=AX4

1003 LLX2=-64.0+LENGTH/2
     LLY2=290.0+WIDTH/2
     LRX2=LLX2+(AX1-1)*LENGTH
     LRY2=LLY2
     URX2=LRX2
     URY2=290.0+((AY1*WIDTH)-WIDTH/2)
     N2=AX11*AY11
     N2R=AX1*AY1
     PPR2=AX1

     IF(AX2.EQ.0)GOTO1004

     LLX3=-64.0+WIDTH/2
     LLY3=500.0-(AY2*LENGTH-LENGTH/2)
     LRX3=LLX3+(AX2-1)*WIDTH
     LRY3=LLY3
     URX3=LRX3
     URY3=500.0-LENGTH/2
     N3=AX22*AY22
     N3R=AX2*AY2
PPR3=AX2

1004 IF(AX3.EQ.0)GOTO1005
```

```
      LLX4=180.0-((AX3*LENGTH)-(LENGTH/2))
      LLY4=500.0-(AY3*WIDTH-WIDTH/2)
      LRX4=180-LENGTH/2
      LRY4=LLY4
      URX4=LRX4
      URY4=500.0-WIDTH/2
      N4=AX33*AY33
      N4R=AX3*AY3
      PPR4=AX3

1005  ENDIF

*************************************************************************
C     OPENING THE AML FILE FOR CREATING THE CONTROL PROGRAM
*************************************************************************
      OPEN(3,FILE='NEW.AML',STATUS='NEW')
*************************************************************************
C     DETERMINE THE # OF LAYERS
*************************************************************************
      LAYER=INT(H/HEIGHT+.5)
*************************************************************************
C     IF DUNNAGE IS REQUESTED, ADD HEIGHT OF DUNNAGE TO Z VALUE FOR
C     EACH LAYER
*************************************************************************
      IF(DUNYES.EQ.1)THEN
      DUNN=-1
      DO 318 I=1,LAYER
      DUNN=DUNN+1
      PT(I)=I*HEIGHT-250.+THICK*DUNN
318    CONTINUE
      ELSE
      DO 319 I=1,LAYER
      PT(I)=I*HEIGHT-250.+HFRAME
319    CONTINUE
      ENDIF
*************************************************************************
C     PUTTING Z VALUES INTO A STRING TO ZAP OF THE BLANKS
*************************************************************************
      DO 30 I=1,LAYER
      WRITE(STR1,320)I,PT(I)
320    FORMAT(1X,'Z ',I3,':',3X,'NEW',1X,F7.2';')
      IF(STR2(3).NE.' ')GOTO 26
      STR3(1)=STR2(1)
      STR3(2)=STR2(2)
      III=3
      DO 321 II =3,12
      IF(STR2(II).NE.' ')GOTO 322
321    CONTINUE
322    CONTINUE
      DO 323 JJ=II,60
      STR3(III)=STR2(JJ)
```

```
      IF(STR2(JJ).EQ.';')GOTO 324
      III=III+1
323   CONTINUE
324   CONTINUE
      WRITE(3,25)(STR3(KK),KK=1,III)
25    FORMAT(60A1)
      GOTO29
26    CONTINUE
      DO 27 III=1,60
      IF(STR2(III).EQ.';')GOTO 28
27    CONTINUE
28    CONTINUE
      WRITE(3,25)(STR2(KK),KK=1,III)
29    CONTINUE
30    CONTINUE
*************************************************************************
C     WRITE GLOBAL PALLET CONST. INTO AML FILE
*************************************************************************
      WRITE(3,31)LLX1,LLY1
31    FORMAT(1X,'LL1: NEW PT(',F7.2,',',F7.2,',0,90);')
      WRITE(3,32)LRX1,LRY1
32    FORMAT(1X,'LR1: NEW PT(',F7.2,',',F7.2,',0,90);')
      WRITE(3,33)URX1,URY1
33    FORMAT(1X,'UR1: NEW PT(',F7.2,',',F7.2,',0,90);')
      WRITE(3,34)N1
34    FORMAT(1X,'N1: NEW ',I3,';')
      WRITE(3,35)N1R
35    FORMAT(1X,'N1REAL: NEW ',I3,';')
      WRITE(3,36)PPR1
36    FORMAT(1X,'PPR1: NEW ',I3,';')

      WRITE(3,37)LLX2,LLY2
37    FORMAT(1X,'LL2: NEW PT(',F7.2,',',F7.2,',0,0);')
      WRITE(3,38)LRX2,LRY2
38    FORMAT(1X,'LR2: NEW PT(',F7.2,',',F7.2,',0,0);')
      WRITE(3,39)URX2,URY2
39    FORMAT(1X,'UR2: NEW PT(',F7.2,',',F7.2,',0,0);')
      WRITE(3,40)N2R
40    FORMAT(1X,'N2REAL: NEW ',I3,';')
      WRITE(3,41)N2
41    FORMAT(1X,'N2: NEW ',I3,';')
      WRITE(3,42)PPR2
42    FORMAT(1X,'PPR2: NEW ',I3,';')

      WRITE(3,43)LLX3,LLY3
43    FORMAT(1X,'LL3: NEW PT(',F7.2,',',F7.2,',0,0);')
      WRITE(3,44)LRX3,LRY3
44    FORMAT(1X,'LR3: NEW PT(',F7.2,',',F7.2,',0,0);')
      WRITE(3,45)URX3,URY3
45    FORMAT(1X,'UR3: NEW PT(',F7.2,',',F7.2,',0,0);')
      WRITE(3,46)N3
```

```
46  FORMAT(1X,'N3: NEW ',I3,';')
    WRITE(3,47)N3R
47  FORMAT(1X,'N3REAL: NEW ',I3,';')
    WRITE(3,48)PPR3
48  FORMAT(1X,'PPR3: NEW ',I3,';')

    WRITE(3,49)LLX4,LLY4
49  FORMAT(1X,'LL4: NEW PT(',F7.2,',',F7.2,',0,90);')
    WRITE(3,50)LRX4,LRY4
50  FORMAT(1X,'LR4: NEW PT(',F7.2,',',F7.2,',0,90);')
    WRITE(3,51)URX4,URY4
51  FORMAT(1X,'UR4: NEW PT(',F7.2,',',F7.2,',0,90);')
    WRITE(3,52)N4R
52  FORMAT(1X,'N4REAL: NEW ',I3,';')
    WRITE(3,53)N4
53  FORMAT(1X,'N4: NEW ',I3,';')

    WRITE(3,54)PPR4
54  FORMAT(1X,'PPR4: NEW ',I3,';')
    WRITE(3,55)LAYER
55  FORMAT(1X,'LAYER: NEW ',I3,';')
*************************************************************************
C   DECLARATION OF DI/DO POINTS
*************************************************************************
    WRITE(3,56)
56  FORMAT(1X,'OPER_ATTNHORN1: NEW 10;')
    WRITE(3,57)
57  FORMAT(1X,'OFF:NEW 0;',/,'OPER_RETRY: NEW 1;',/,'ON:NEW 1;',/
   *'OPER_ATTNHORN: NEW 11;',/,'PORT: NEW 5;')

*************************************************************************
C   WRITING GLOBAL VARIABLES INTO AML FILE
*************************************************************************
    WRITE(3,58)
58  FORMAT(1X,'PITT: STATIC COUNTER;',/,'TURN :STATIC COUNTER;')
    WRITE(3,59)
59  FORMAT(1X,'SAMPLE1: STATIC PALLET(LL1,LR1,UR1,PPR1,N1);')
    WRITE(3,60)
60  FORMAT(1X,'SAMPLE2: STATIC PALLET(LL2,LR2,UR2,PPR2,N2);')
    WRITE(3,61)
61  FORMAT(1X,'SAMPLE3: STATIC PALLET(LL3,LR3,UR3,PPR3,N3);')
    WRITE(3,62)
62  FORMAT(1X,'SAMPLE4: STATIC PALLET(LL4,LR4,UR4,PPR4,N4);')
    WRITE(3,63)INTERX,INTERY,INTERZ,INTERR,SEMIX,SEMIY,
   *SEMIZ,SEMIR,MATE,CARLX,CARLY,CARLZ,CARLR
63  FORMAT(1X,'INTER:NEW PT(',F7.2,',',F7.2,',',F7.2,',',F7.2,');',/
   *'SEMI:NEW PT(',F7.2,',',F7.2,',',F7.2,',',F7.2,');',/
   *'RESTART:NEW 5;',/,'MATE: NEW ',F7.2,';',/,'ZYLINDER1: NEW 1;',/
   *'ZYLINDER2: NEW 5;',/,'STEP: NEW 16;',/,'HOME1: NEW 9;',/
   *'CAROUSSEL: NEW PT(',F7.2,',',F7.2,',',F7.2,',',F7.2,');',/
   *'PALLET_CENTER: NEW PT(0,0,0,0);',/
```

```
     *'DUNN_PICKUP: NEW PT(0,0,0,0);')
      WRITE(3,64)PICKZ
64    FORMAT(1X,'PICKZ: NEW ',F7.2,';')
      WRITE(3,65)PICKX,PICKY
65    FORMAT(1X,'PICKY: NEW PT(',F7.2,',',F7.2,',0,0 );')
*******************************************************************************
C     HEIGHT OF DUNNAGE PILE AFTER EACH LAYER
*******************************************************************************
      DO 67 I=1,LAYER
      DUZ(I)=PT(I)+THICK
      WRITE(3,66)I,DUZ(I)
66    FORMAT(1X,'DUZ',I1,':NEW',F7.2,';')
67    CONTINUE
*******************************************************************************
C     START OF THE MAIN SUBROUTINE
*******************************************************************************
      WRITE(3,68)
68    FORMAT(1X,'MAINPROG:SUBR;')
*******************************************************************************
C     SET_HOME SUBROUTINE TURNS THE CROUSSEL TO KNOWN POSITION
*******************************************************************************
      WRITE(3,69)
69    FORMAT(1X,'SET_HOME:SUBR;')
      WRITE(3,70)
70    FORMAT(1X,'LOOP:WRITEO(STEP,OFF);DELAY(0.1);WRITEO(STEP,ON);',/
     *'DELAY(0.1);TESTI(HOME1,ON,DONE);',/
     *'BRANCH(LOOP);',/,'DONE:BREAKPOINT;',/,'END;')
*******************************************************************************
C     ROTATE SUBROUTINE ROTATES THE CAROUSSEL TO THE REQUESTED DEGREE
*******************************************************************************
      WRITE(3,71)
71    FORMAT(1X,'ROTATE:SUBR(DEGREE);')
      WRITE(3,72)
72    FORMAT(1X,'SETC(TURN,1);LOOP:WRITEO(STEP,OFF);DELAY(0.1);',/
     *'WRITEO(STEP,ON);DELAY(0.1);',/
     *'TESTC(TURN,DEGREE,DONE);',/,'INCR(TURN);BRANCH(LOOP);',/
     *'DONE:BREAKPOINT;',/,'END;')

      IF(WEIGHT.EQ.1)THEN
*******************************************************************************
C     IF SHIPPER WEIGHT IS IN THE RANGE OF 0 - 5 LB, THE ROBOT WILL
C     PICK UP THE SMALL VACUUM GRIPPER
*******************************************************************************
      WRITE(3,73)
73    FORMAT(1X,'INTERCHANGE_BEGIN_REG:SUBR;')
      WRITE(3,74)
74    FORMAT(1X,'PMOVE(INTER);SET_HOME;PAYLOAD(11);ZONE(1);',/
     *'ZMOVE(MATE);WRITEO(ZYLINDER1,ON);DELAY(2);PMOVE(SEMI);',/
     *'WRITEO(15,ON);ZONE(0);PAYLOAD(0);',/
     *'ZMOVE(0);WRITEO(15,ON);END;')
      ELSE
```

```
*************************************************************************
C   IF SHIPPER WEIGHT IS IN THE RANGE OF 5 - 10 LB, THE ROBOT WILL
C   PICK UP THE BIG VACUUM GRIPPER
*************************************************************************
    WRITE(3,75)
75  FORMAT(1X,'INTERCHANGE_BEGIN_HEAVY:SUBR;')
    WRITE(3,76)
76  FORMAT(1X,'PMOVE(INTER);PAYLOAD(11);SET_HOME;ROTATE(25);',/
   *'ZONE(1);ZMOVE(MATE);WRITEO(ZYLINDER1,ON);ZONE(0);',/
   *'DELAY(2);PMOVE(SEMI);LINEAR(0);',/,'WRITEO(15,ON);',/
   *'PAYLOAD(0);ZMOVE(0);WRITEO(15,ON);',/,'END;')
    ENDIF
    IF(DUNYES.EQ.1.AND.WEIGHT.EQ.1)THEN
*************************************************************************
C   DUNN_GRIPPER_ROTATE SUBROUTINE ROTATES THE CAROUSSEL TO ENABLE
C   THE ROBOT TO PICK UP THE DUNNAGE GRIPPER
*************************************************************************
    WRITE(3,77)
77  FORMAT(1X,'DUNN_GRIPPER_ROTATE:SUBR(PLACE5);')
    WRITE(3,78)
78  FORMAT(1X,'PMOVE(SEMI);LINEAR(1);SET_HOME;PMOVE(CAROUSSEL);',/
   *'WRITEO(ZYLINDER1,OFF);DELAY(2);WRITEO(ZYLINDER2,ON);',/
   *'DELAY(4);WRITEO(ZYLINDER2,OFF);DELAY(5);ZMOVE(0);',/
   *'ROTATE(100);DELAY(2);ZMOVE(MATE);WRITEO(ZYLINDER1,ON);',/
   *'DELAY(2);PMOVE(SEMI);LINEAR(0);PMOVE(DUNN_PICKUP);',/
   *'GRASP;DELAY(1);PMOVE(PALLET_CENTER);GUARDI(8,ON);',/
   *'ZMOVE(PLACE5);NOGUARD;RELEASE;DELAY(1);ZMOVE(0);',/
   *'PMOVE(SEMI);LINEAR(1);SET_HOME;ROTATE(50);PMOVE(CAROUSSEL);',/
   *'WRITEO(ZYLINDER1,OFF);DELAY(2);WRITEO(ZYLINDER2,ON);',/
   *'DELAY(4);WRITEO(ZYLINDER2,OFF);DELAY(5);ZMOVE(0);',/
   *'SET_HOME;DELAY(2);ZMOVE(MATE);WRITEO(ZYLINDER1,ON);',/
   *'DELAY(2);PMOVE(SEMI);LINEAR(0);',/,'END;')
    ENDIF

    IF(DUNYES.EQ.1.AND.WEIGHT.NE.1)THEN
    WRITE(3,79)
79  FORMAT(1X,'DUNN_GRIPPER_ROTATE:SUBR(PLACE5);')
    WRITE(3,80)
80  FORMAT(1X,'PMOVE(SEMI);LINEAR(1);SET_HOME;',/
   *'ROTATE(25);PMOVE(CAROUSSEL);',/
   *'WRITEO(ZYLINDER1,OFF);DELAY(2);WRITEO(ZYLINDER2,ON);',/
   *'DELAY(4);WRITEO(ZYLINDER2,OFF);DELAY(5);ZMOVE(0);',/
   *'ROTATE(25);DELAY(2);ZMOVE(MATE);WRITEO(ZYLINDER1,ON);',/
   *'DELAY(2);PMOVE(SEMI);LINEAR(0);PMOVE(DUNN_PICKUP);',/
   *'GRASP;DELAY(1);PMOVE(PALLET_CENTER);GUARDI(8,ON);',/
   *'ZMOVE(PLACE5);NOGUARD;RELEASE;DELAY(1);ZMOVE(0);',/
   *'PMOVE(SEMI);LINEAR(1);SET_HOME;ROTATE(50);PMOVE(CAROUSSEL);',/
   *'WRITEO(ZYLINDER1,OFF);DELAY(2);WRITEO(ZYLINDER2,ON);',/
   *'DELAY(4);WRITEO(ZYLINDER2,OFF);DELAY(5);ZMOVE(0);',/
   *'ROTATE(150);DELAY(2);ZMOVE(MATE);WRITEO(ZYLINDER1,ON);',/
   *'DELAY(2);PMOVE(SEMI);LINEAR(0);',/,'END;')
```

```
      ENDIF
*************************************************************************
C     WAIT_PART SUBROUTINE SIGNALS THE CONTROLLER WHEN A PART IS
C     PRESENT AT THE PICK UP STATION, IF A PART DOES NOT ARRIVE
C     AFTER 15 SEC., THE OPERATER WILL BE WARNED
*************************************************************************
      WRITE(3,81)
81    FORMAT(1X,'WAIT_PART:SUBR;',/,'WAITI(PORT,ON,15,TROUBLE);',/
     *'BRANCH(DONE);',/,'TROUBLE:WRITEO(OPER_ATTNHORN,ON);',/
     *'WAITI(OPER_RETRY,OFF,0);WAITI(OPER_RETRY,ON,0);',/
     *'WAITI(OPER_RETRY,OFF,0);WRITEO(OPER_ATTNHORN,OFF);',/
     *'DONE:BREAKPOINT;',/,'END;')
*************************************************************************
C     NEW_PALLET SUBROUTINE WILL WARN THE OPERATER THAT THE CURRENT
C     PALLET IS STACKED TO CAPACITY AND GIVES HIM/HER 20 SEC. TO
C     REPLACE THE CURRENT PALLET WITH AN EMPTY ONE. IF PALLET IS
C     NOT REPLACED, THE ROBOT WILL PARK THE GRIPPER AND WAITS TO
C     BE RESTARTED.
*************************************************************************
      IF(WEIGHT.EQ.1)THEN
      WRITE(3,82)
82    FORMAT(1X,'NEW_PALLET:SUBR;',/,'WRITEO(OPER_ATTNHORN1,ON);',/
     *'WAITI(OPER_RETRY,OFF,5);WAITI(OPER_RETRY,ON,10,LOOP_PARK);',/
     *'WAITI(OPER_RETRY,OFF,10);',/,'WRITEO(OPER_ATTNHORN1,OFF);',/
     *'BRANCH(DONE);',/,'LOOP_PARK:ZMOVE(0);PMOVE(SEMI);LINEAR(1);',/
     *'WRITEO(OPER_ATTNHORN1,OFF);WRITEO(15,OFF);SET_HOME;',/
     *'PMOVE(CAROUSSEL);WRITEO(ZYLINDER1,OFF);DELAY(3);',/
     *'WRITEO(ZYLINDER2,ON);DELAY(3);WRITEO(ZYLINDER2,OFF);',/
     *'DELAY(5);LINEAR(1);ZMOVE(-150);LINEAR(0);ZMOVE(0);',/
     *'DONE:BREAKPOINT;WRITEO(OPER_ATTNHORN1,OFF);',/
     *'PMOVE(PT(650,0,0,0));',/,'END;')
      ELSE
      WRITE(3,83)
83    FORMAT(1X,'NEW_PALLET:SUBR;',/,'WRITEO(OPER_ATTNHORN1,ON);',/
     *'WAITI(OPER_RETRY,OFF,5);WAITI(OPER_RETRY,ON,10,LOOP_PARK);',/
     *'WAITI(OPER_RETRY,OFF,10);',/,'WRITEO(OPER_ATTNHORN1,OFF);',/
     *'BRANCH(DONE);',/,'LOOP_PARK:ZMOVE(0);PMOVE(SEMI);LINEAR(1);',/
     *'WRITEO(15,OFF);WRITEO(OPER_ATTNHORN1,OFF);SET_HOME;ROTATE(25);',/
     *'PMOVE(CAROUSSEL);WRITEO(ZYLINDER1,OFF);DELAY(3);',/
     *'WRITEO(ZYLINDER2,ON);DELAY(3);WRITEO(ZYLINDER2,OFF);',/
     *'DELAY(5);LINEAR(1);ZMOVE(-150);LINEAR(0);ZMOVE(0);',/
     *'DONE:BREAKPOINT;WRITEO(OPER_ATTNHORN1,OFF);',/
     *'PMOVE(PT(650,0,0,0));',/,'END;')
       ENDIF
*************************************************************************
C     PICKUP SUBROUTINE STACKS THE FIRST PART OF EVERY ODD LAYER
*************************************************************************
      WRITE(3,84)
84    FORMAT(1X,'PICKUP:SUBR(PLACE1);')
      WRITE(3,85)
85    FORMAT(1X,'SET: SETPART(SAMPLE1,1);')
```

```
      WRITE(3,86)
86    FORMAT(1X,'LOOP:WAIT_PART;PMOVE(PICKY);ZMOVE(PICKZ);')
      WRITE(3,87)
87    FORMAT(1X,'GRASP;DELAY(1);ZMOVE(0);')
      WRITE(3,88)
88    FORMAT(1X,'GETPART(SAMPLE1);GUARDI(8,1);ZMOVE(PLACE1);',/
     *'NOGUARD;RELEASE;DELAY(1);')
      WRITE(3,89)
89    FORMAT(1X,'ZMOVE(0);TESTP(SAMPLE1,N1REAL,DONE);')
      WRITE(3,90)
90    FORMAT(1X,'NEXTPART(SAMPLE1);')
      WRITE(3,91)
91    FORMAT(1X,'BRANCH(LOOP);')
      WRITE(3,92 )
92    FORMAT(1X,'DONE:BREAKPOINT;')
      WRITE(3,93)
93    FORMAT(1X,'END;')
*************************************************************************
C     OLDPR SUBROUTINE STACKS THE SECOND PART OF EVERY ODD LAYER
*************************************************************************
      WRITE(3,94)
94    FORMAT(1X,'OLDPR:SUBR(PLACE2);')
      WRITE(3,95)
95    FORMAT(1X,'SET: SETPART(SAMPLE2,1);')
      WRITE(3,96)
96    FORMAT(1X,'LOOP:WAIT_PART;PMOVE(PICKY);ZMOVE(PICKZ);')
      WRITE(3,97)
97    FORMAT(1X,'GRASP;DELAY(1);ZMOVE(0);')
      WRITE(3,98)
98    FORMAT(1X,'GETPART(SAMPLE2);GUARDI(8,1);ZMOVE(PLACE2);',/
     *'NOGUARD;RELEASE;DELAY(1);')
      WRITE(3,99)
99    FORMAT(1X,'ZMOVE(0);TESTP(SAMPLE2,N2REAL,DONE);')
      WRITE(3,100)
100   FORMAT(1X,'NEXTPART(SAMPLE2);')
      WRITE(3,101)
101   FORMAT(1X,'BRANCH(LOOP);')
      WRITE(3,102)
102   FORMAT(1X,'DONE:BREAKPOINT;')
      WRITE(3,103)
103   FORMAT(1X,'END;')
*************************************************************************
C     NEWPR SUBROUTINE STACKS THE FIRST PART OF EVERY EVEN LAYER
*************************************************************************
      WRITE(3,104)
104   FORMAT(1X,'NEWPR:SUBR(PLACE3);')
      WRITE(3,105)
105   FORMAT(1X,'SET: SETPART(SAMPLE3,1);')
      WRITE(3,106)
106   FORMAT(1X,'LOOP:WAIT_PART;PMOVE(PICKY);ZMOVE(PICKZ);')
      WRITE(3,107)
```

```
107 FORMAT(1X,'GRASP;DELAY(1);ZMOVE(0);')
    WRITE(3,108)
108 FORMAT(1X,'GETPART(SAMPLE3);GUARDI(8,1);ZMOVE(PLACE3);',/
   *'NOGUARD;RELEASE;DELAY(1);')
    WRITE(3,109)
109 FORMAT(1X,'ZMOVE(0);TESTP(SAMPLE3,N3REAL,DONE);')
    WRITE(3,110)
110 FORMAT(1X,'NEXTPART(SAMPLE3);')
    WRITE(3,111)
111 FORMAT(1X,'BRANCH(LOOP);')
    WRITE(3,112)
112 FORMAT(1X,'DONE:BREAKPOINT;')
    WRITE(3,113)
113 FORMAT(1X,'END;')
*************************************************************************
C   LAST PROGRAM STACKS THE SECOND PART OF EVERY EVEN LAYER
*************************************************************************
    WRITE(3,114)
114 FORMAT(1X,'LAST:SUBR(PLACE4);')
    WRITE(3,115)
115 FORMAT(1X,'SET: SETPART(SAMPLE4,1);')
    WRITE(3,116)
116 FORMAT(1X,'LOOP:WAIT_PART;PMOVE(PICKY);ZMOVE(PICKZ);')
    WRITE(3,117)
117 FORMAT(1X,'GRASP;DELAY(1);ZMOVE(0);')
    WRITE(3,118)
118 FORMAT(1X,'GETPART(SAMPLE4);GUARDI(8,1);ZMOVE(PLACE4);',/
   *'NOGUARD;RELEASE;DELAY(1);')
    WRITE(3,119)
119 FORMAT(1X,'ZMOVE(0);TESTP(SAMPLE4,N4REAL,DONE);')
    WRITE(3,120)
120 FORMAT(1X,'NEXTPART(SAMPLE4);')
    WRITE(3,121)
121 FORMAT(1X,'BRANCH(LOOP);')
    WRITE(3,122)
122  FORMAT(1X,'DONE:BREAKPOINT;')
    WRITE(3,123)
123  FORMAT(1X,'END;')
    I=1
*************************************************************************
C   CALLING THE DIFFERENT SUBROUTINES FOR ALL DIFFERENT CASES
*************************************************************************
    IF(DUNYES.EQ.1)THEN
    IF(WEIGHT.EQ.1)THEN
    WRITE(3,124)
124 FORMAT(1X,'INTERCHANGE_BEGIN_REG;')
    ELSE
    WRITE(3,125)
125 FORMAT(1X,'INTERCHANGE_BEGIN_HEAVY;')
    ENDIF
    WW=1
```

```
      WRITE(3,126)
  126 FORMAT(1X,'OVER:SETC(PITT,0);')

  127 CONTINUE

      IF(I.LE.4)THEN

      WRITE(3,128)I
  128 FORMAT(1X,'PICKUP(Z',I1,');')

      WRITE(3,129)I
  129 FORMAT(1X,'OLDPR(Z',I1,');')
      WRITE(3,133)I
  133 FORMAT(1X,'NEWPR(Z',I1,');')

      WRITE(3,134)I
  134  FORMAT(1X,'LAST(Z',I1,');')
      WRITE(3,135)
  135 FORMAT(1X,'INCR(PITT);')
      WRITE(3,136)WW,WW+1,WW,WW+1,I
  136 FORMAT(1X,'TESTC(PITT,LAYER,LOOP',I1,');',/
     *'BRANCH(LOOP',I1,');',/,'LOOP',I1,':NEW_PALLET;',/
     *'WAITI(RESTART,OFF,0);WAITI(RESTART,ON,0);WAITI(RESTART,OFF,0);',/
     *'BRANCH(OVER);',/,'LOOP',I1,':DUNN_GRIPPER_ROTATE(DUZ',I1,');')
      WW=WW+2
      IF(I.EQ.LAYER)GOTO168
      I=I+1
      GOTO127

      ELSE
      WW=WW+4
  137 WRITE(3,138)I
  138 FORMAT(1X,'PICKUP(Z',I1,');')
      IF(N2R.EQ.0)GOTO140
      WRITE(3,139)I
  139 FORMAT(1X,'OLDPR(Z',I1,');')
  140 IF(N3R.EQ.0)GOTO141
      WRITE(3,142)I
  142 FORMAT(1X,'NEWPR(Z',I1,');')

  141 WRITE(3,143)I
  143 FORMAT(1X,'LAST(Z',I1,');')
      WRITE(3,144)
  144 FORMAT(1X,'INCR(PITT);')
      WRITE(3,145)WW,WW+1,WW,WW+1,I
  145 FORMAT(1X,'TESTC(PITT,LAYER,LOOP',I2,');',/
     *'BRANCH(LOOP',I2,');',/,'LOOP',I2,':NEW_PALLET;',/
     *'BRANCH(OVER);',/,'LOOP',I2,':DUNN_GRIPPER_ROTATE(DUZ',I1,');')
      WW=WW+2
      IF(I.EQ.LAYER)GOTO168
      I=I+1
```

```
    GOTO137
    ENDIF

    ELSE

    WW=1
    IF(WEIGHT.EQ.1)THEN
    WRITE(3,146)
146 FORMAT(1X,'INTERCHANGE_BEGIN_REG;')
    ELSE
    WRITE(3,147)
147 FORMAT(1X,'INTERCHANGE_BEGIN_HEAVY;')
    ENDIF

    WRITE(3,148)
148 FORMAT(1X,'OVER:SETC(PITT,0);')

149 CONTINUE

    IF(I.LE.4)THEN

    WRITE(3,150)I
150 FORMAT(1X,'PICKUP(Z',I1,');')
    IF(N2R.EQ.0)GOTO 152
    WRITE(3,151)I
151 FORMAT(1X,'OLDPR(Z',I1,');')
152 IF(N3R.EQ.0)GOTO155
    WRITE(3,154)I
154 FORMAT(1X,'NEWPR(Z',I1,');')

155 WRITE(3,156)I
156 FORMAT(1X,'LAST(Z',I1,');')

    WRITE(3,157)
157 FORMAT(1X,'INCR(PITT);')
    WRITE(3,158)WW,WW+1,WW
158 FORMAT(1X,'TESTC(PITT,LAYER,LOOP',I1,');',/
   *'BRANCH(LOOP',,I1,');',/,'LOOP',I1,':NEW_PALLET;',/
   *'WAITI(RESTART,OFF,0);WAITI(RESTART,ON,0);WAITI(RESTART,OFF,0);',/
   *'BRANCH(OVER);')
    WRITE(3,159)WW+1
159 FORMAT(1X,'LOOP',I1,':DELAY(1);')
    IF(I.EQ.LAYER)GOTO168
    WW=WW+2
    I=I+1
    GOTO149

    ELSE
    WW=WW+4
    WRITE(3,160)I
160 FORMAT(1X,'PICKUP(Z',I1,');')
```

```
      WRITE(3,161)I
      IF(N2R.EQ.0)GOTO180
  161 FORMAT(1X,'OPDPR(Z',I1,');')
  180 IF(N3R.EQ.0)GOTO181
      WRITE(3,162)I
  162 FORMAT(1X,'NEWPR(Z',I1,');')

  181 WRITE(3,163)I
  163 FORMAT(1X,'LAST(Z',I1,');')

      WRITE(3,164)
  164 FORMAT(1X,'INCR(PITT);')
      WRITE(3,165)WW,WW+1,WW
  165 FORMAT(1X,'TESTC(PITT,LAYER,LOOP',I2,');',/
     *'BRANCH(LOOP',,I2,');',/,'LOOP',I2,':NEW_PALLET;',/
     *'WAITI(RESTART,OFF,0);WAITI(RESTART,ON,0);WAITI(RESTART,OFF,0);',/
     *'BRANCH(OVER);')

      WRITE(3,166)WW+1
  166 FORMAT(1X,'LOOP',I2,':DELAY(1);')
      IF(I.EQ.LAYER)GOTO168
      WW=WW+2
      I=I+1
      GOTO149

      ENDIF
      ENDIF
  167 CONTINUE
  168 WRITE(3,169)
  169 FORMAT(1X,'END;')
  170 STOP
      END
*******************************************************************************
CSUBROUTINE TO INTERACTIVELY COMMUNICATE WITH THE USER
*******************************************************************************
      SUBROUTINE PRINT (ROW,COL,STRING,LENGT)
      INTEGER PAGE, ROW, COL, LENGT, CHAR
      CHARACTER STRING(LENGT)
      CALL CURPAG(PAGE)
      CALL LOCATE(PAGE,ROW,COL)
      DO 171 I=1,LENGT
      CHAR=ICHAR(STRING(I))
      CALL WRTTY(CHAR)
  171 CONTINUE
      RETURN
      END
```

APPENDIX C

AML/E PROGRAM

```
 Z1:   NEW -224.60;
 Z2:   NEW -194.12;
 Z3:   NEW -163.64;
 LL1: NEW PT( -23.36, 320.48,0,90);
 LR1: NEW PT( 139.36, 320.48,0,90);
 UR1: NEW PT( 139.36, 381.44,0,90);
 N1: NEW   6;
 N1REAL: NEW   6;
 PPR1: NEW   3;
 LL2: NEW PT( -33.52, 458.06,0,0);
 LR2: NEW PT( 159.52, 458.06,0,0);
 UR2: NEW PT( 159.52, 467.06,0,0);
 N2REAL: NEW   4;
 N2: NEW   8;
 PPR2: NEW   4;
 LL3: NEW PT( -33.52, 336.14,0,0);
 LR3: NEW PT( 159.52, 336.14,0,0);
 UR3: NEW PT( 159.52, 336.14,0,0);
 N3: NEW   8;
 N3REAL: NEW   4;
 PPR3: NEW   4;
 LL4: NEW PT( -23.36, 407.26,0,90);
 LR4: NEW PT( 139.36, 407.26,0,90);
 UR4: NEW PT( 139.36, 468.22,0,90);
 N4: NEW   6;
 N4REAL: NEW   6;
 PPR4: NEW   3;
 LAYER: NEW   3;
 OPER_ATTNHORN1: NEW 10;
 OFF:NEW 0;
OPER_RETRY: NEW 1;
ON:NEW 1;
OPER_ATTNHORN: NEW 11;
PORT: NEW 5;
 PITT: STATIC COUNTER;
TURN :STATIC COUNTER;
 SAMPLE1: STATIC PALLET(LL1,LR1,UR1,PPR1,N1);
 SAMPLE2: STATIC PALLET(LL2,LR2,UR2,PPR2,N2);
 SAMPLE3: STATIC PALLET(LL3,LR3,UR3,PPR3,N3);
 SAMPLE4: STATIC PALLET(LL4,LR4,UR4,PPR4,N4);
 INTER:NEW PT(-401.00,-318.30,    .00,  54.00);
SEMI:NEW PT(-401.00,-200.00,-212.00,  54.00);
RESTART:NEW 5;
MATE: NEW -214.60;
ZYLINDER1: NEW 1;
ZYLINDER2: NEW 5;
STEP: NEW 16;
HOME1: NEW 9;
CAROUSSEL: NEW PT(-401.00,-318.30,-212.00,  54.00);
PALLET_CENTER: NEW PT(0,0,0,0);
DUNN_PICKUP: NEW PT(0,0,0,0);
```

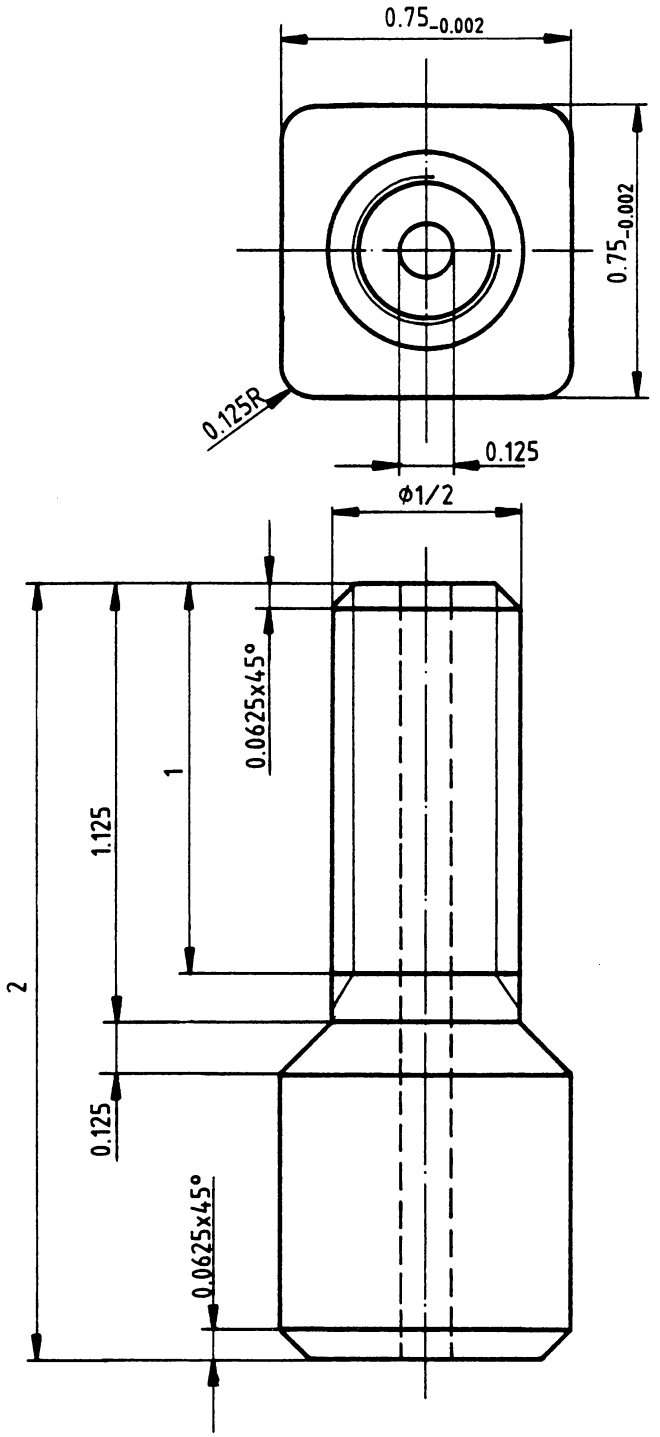
```
 PICKZ: NEW -162.00;
 PICKY: NEW PT( 400.00, 400.00,0,0 );
 DUZ1:NEW-219.52;
 DUZ2:NEW-189.04;
 DUZ3:NEW-158.56;
 MAINPROG:SUBR;
 SET_HOME:SUBR;
 LOOP:WRITEO(STEP,OFF);DELAY(0.1);WRITEO(STEP,ON);
DELAY(0.1);TESTI(HOME1,ON,DONE);
BRANCH(LOOP);
DONE:BREAKPOINT;
END;
 ROTATE:SUBR(DEGREE);
 SETC(TURN,1);LOOP:WRITEO(STEP,OFF);DELAY(0.1);
WRITEO(STEP,ON);DELAY(0.1);
TESTC(TURN,DEGREE,DONE);
INCR(TURN);BRANCH(LOOP);
DONE:BREAKPOINT;
END;
 INTERCHANGE_BEGIN_REG:SUBR;
 PMOVE(INTER);SET_HOME;PAYLOAD(11);ZONE(1);
ZMOVE(MATE);WRITEO(ZYLINDER1,ON);DELAY(2);PMOVE(SEMI);
WRITEO(15,ON);ZONE(0);PAYLOAD(0);
ZMOVE(0);WRITEO(15,ON);END;
 DUNN_GRIPPER_ROTATE:SUBR(PLACE5);
 PMOVE(SEMI);LINEAR(1);SET_HOME;PMOVE(CAROUSSEL);
WRITEO(ZYLINDER1,OFF);DELAY(2);WRITEO(ZYLINDER2,ON);
DELAY(4);WRITEO(ZYLINDER2,OFF);DELAY(5);ZMOVE(0);
ROTATE(100);DELAY(2);ZMOVE(MATE);WRITEO(ZYLINDER1,ON);
DELAY(2);PMOVE(SEMI);LINEAR(0);PMOVE(DUNN_PICKUP);
GRASP;DELAY(1);PMOVE(PALLET_CENTER);GUARDI(8,ON);
ZMOVE(PLACE5);NOGUARD;RELEASE;DELAY(1);ZMOVE(0);
PMOVE(SEMI);LINEAR(1);SET_HOME;ROTATE(50);PMOVE(CAROUSSEL);
WRITEO(ZYLINDER1,OFF);DELAY(2);WRITEO(ZYLINDER2,ON);
DELAY(4);WRITEO(ZYLINDER2,OFF);DELAY(5);ZMOVE(0);
SET_HOME;DELAY(2);ZMOVE(MATE);WRITEO(ZYLINDER1,ON);
DELAY(2);PMOVE(SEMI);LINEAR(0);
END;
 WAIT_PART:SUBR;
WAITI(PORT,ON,15,TROUBLE);
BRANCH(DONE);
TROUBLE:WRITEO(OPER_ATTNHORN,ON);
WAITI(OPER_RETRY,OFF,0);WAITI(OPER_RETRY,ON,0);
WAITI(OPER_RETRY,OFF,0);WRITEO(OPER_ATTNHORN,OFF);
DONE:BREAKPOINT;
END;
 NEW_PALLET:SUBR;
WRITEO(OPER_ATTNHORN1,ON);
WAITI(OPER_RETRY,OFF,5);WAITI(OPER_RETRY,ON,10,LOOP_PARK);
WAITI(OPER_RETRY,OFF,10);
WRITEO(OPER_ATTNHORN1,OFF);
```

```
BRANCH(DONE);
LOOP_PARK:ZMOVE(0);PMOVE(SEMI);LINEAR(1);
WRITEO(OPER_ATTNHORN1,OFF);WRITEO(15,OFF);SET_HOME;
PMOVE(CAROUSSEL);WRITEO(ZYLINDER1,OFF);DELAY(3);
WRITEO(ZYLINDER2,ON);DELAY(3);WRITEO(ZYLINDER2,OFF);
DELAY(5);LINEAR(1);ZMOVE(-150);LINEAR(0);ZMOVE(0);
DONE:BREAKPOINT;WRITEO(OPER_ATTNHORN1,OFF);
PMOVE(PT(650,0,0,0));
END;
 PICKUP:SUBR(PLACE1);
 SET: SETPART(SAMPLE1,1);
 LOOP:WAIT_PART;PMOVE(PICKY);ZMOVE(PICKZ);
 GRASP;DELAY(1);ZMOVE(0);
 GETPART(SAMPLE1);GUARDI(8,1);ZMOVE(PLACE1);
NOGUARD;RELEASE;DELAY(1);
 ZMOVE(0);TESTP(SAMPLE1,N1REAL,DONE);
 NEXTPART(SAMPLE1);
 BRANCH(LOOP);
 DONE:BREAKPOINT;
 END;
 OLDPR:SUBR(PLACE2);
 SET: SETPART(SAMPLE2,1);
 LOOP:WAIT_PART;PMOVE(PICKY);ZMOVE(PICKZ);
 GRASP;DELAY(1);ZMOVE(0);
 GETPART(SAMPLE2);GUARDI(8,1);ZMOVE(PLACE2);
NOGUARD;RELEASE;DELAY(1);
 ZMOVE(0);TESTP(SAMPLE2,N2REAL,DONE);
 NEXTPART(SAMPLE2);
 BRANCH(LOOP);
 DONE:BREAKPOINT;
 END;
 NEWPR:SUBR(PLACE3);
 SET: SETPART(SAMPLE3,1);
 LOOP:WAIT_PART;PMOVE(PICKY);ZMOVE(PICKZ);
 GRASP;DELAY(1);ZMOVE(0);
 GETPART(SAMPLE3);GUARDI(8,1);ZMOVE(PLACE3);
NOGUARD;RELEASE;DELAY(1);
 ZMOVE(0);TESTP(SAMPLE3,N3REAL,DONE);
 NEXTPART(SAMPLE3);
 BRANCH(LOOP);
 DONE:BREAKPOINT;
 END;
 LAST:SUBR(PLACE4);
 SET: SETPART(SAMPLE4,1);
 LOOP:WAIT_PART;PMOVE(PICKY);ZMOVE(PICKZ);
 GRASP;DELAY(1);ZMOVE(0);
 GETPART(SAMPLE4);GUARDI(8,1);ZMOVE(PLACE4);
NOGUARD;RELEASE;DELAY(1);
 ZMOVE(0);TESTP(SAMPLE4,N4REAL,DONE);
 NEXTPART(SAMPLE4);
 BRANCH(LOOP);
```

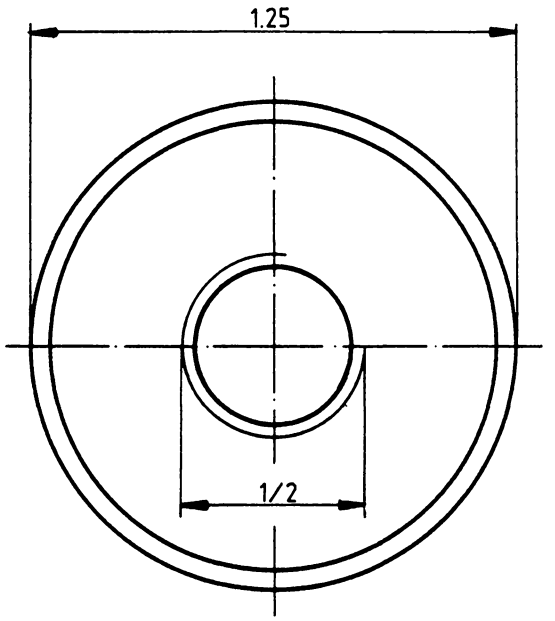
```
 DONE:BREAKPOINT;
 END;
 INTERCHANGE_BEGIN_REG;
 OVER:SETC(PITT,0);
 PICKUP(Z1);
 OLDPR(Z1);
 INCR(PITT);
 TESTC(PITT,LAYER,LOOP1);
BRANCH(LOOP2);
LOOP1:NEW_PALLET;
WAITI(RESTART,OFF,0);WAITI(RESTART,ON,0);WAITI(RESTART,OFF,0);
BRANCH(OVER);
 LOOP2:DUNN_GRIPPER_ROTATE(DUZ1);
 NEWPR(Z2);
 LAST(Z2);
 INCR(PITT);
 TESTC(PITT,LAYER,LOOP3);
BRANCH(LOOP4);
LOOP3:NEW_PALLET;
WAITI(RESTART,OFF,0);WAITI(RESTART,ON,0);WAITI(RESTART,OFF,0);
BRANCH(OVER);
LOOP4:DUNN_GRIPPER_ROTATE(DUZ2);
 PICKUP(Z3);
 OLDPR(Z3);
 INCR(PITT);
 TESTC(PITT,LAYER,LOOP5);
BRANCH(LOOP6);
LOOP5:NEW_PALLET;
WAITI(RESTART,OFF,0);WAITI(RESTART,ON,0);WAITI(RESTART,OFF,0);
BRANCH(OVER);
 LOOP6:DUNN_GRIPPER_ROTATE(DUZ3);
 END;
```

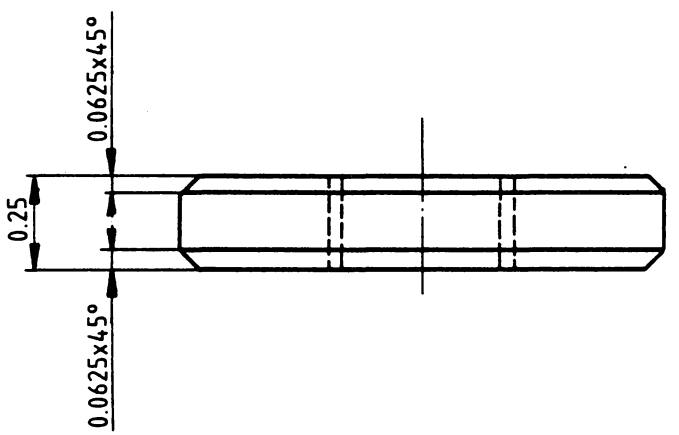
APPENDIX D

MECHANICAL DRAWINGS

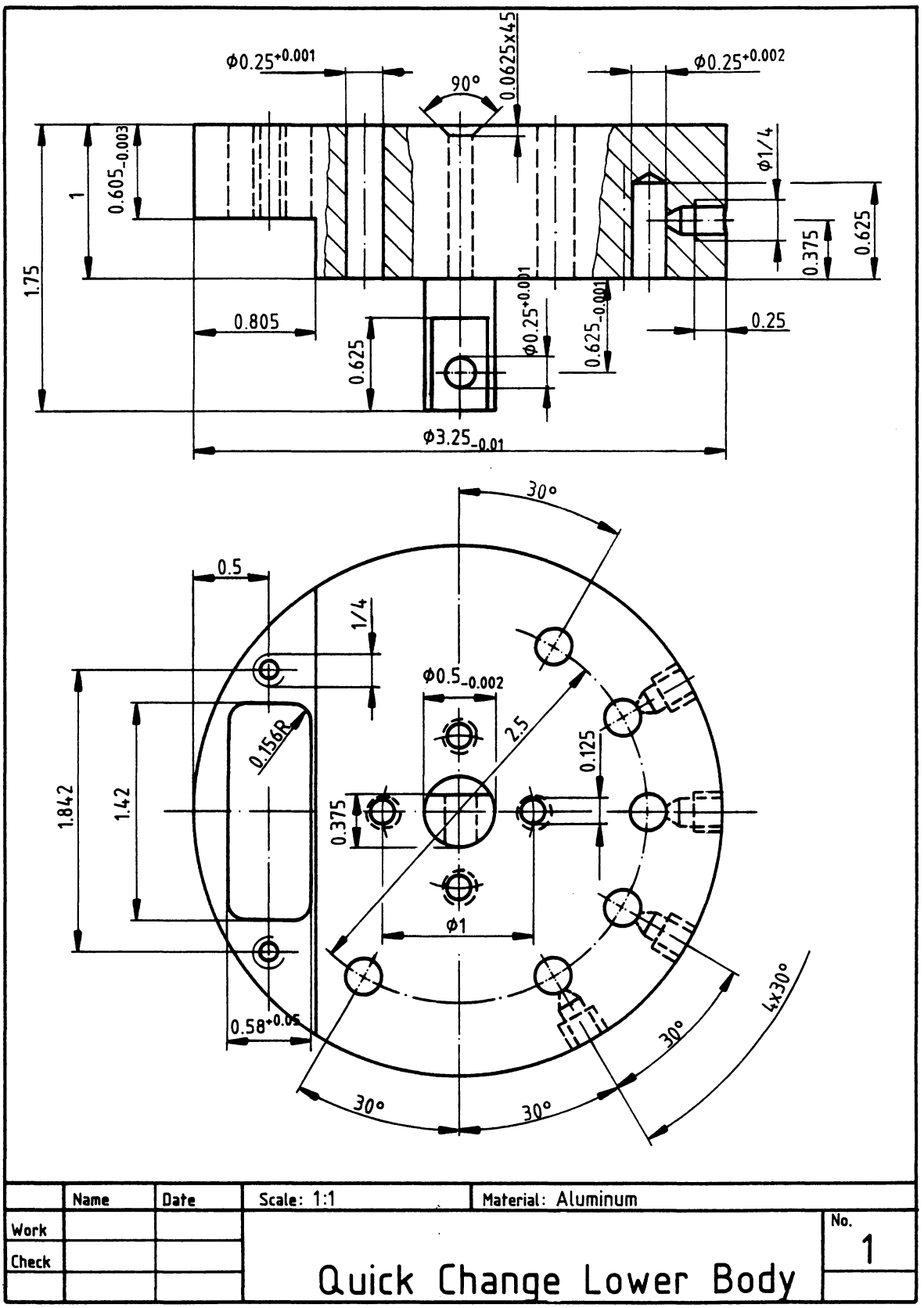


	Name	Date	Scale: 2:1	Material: Aluminum	
Work			Piston		No. 2
Check					

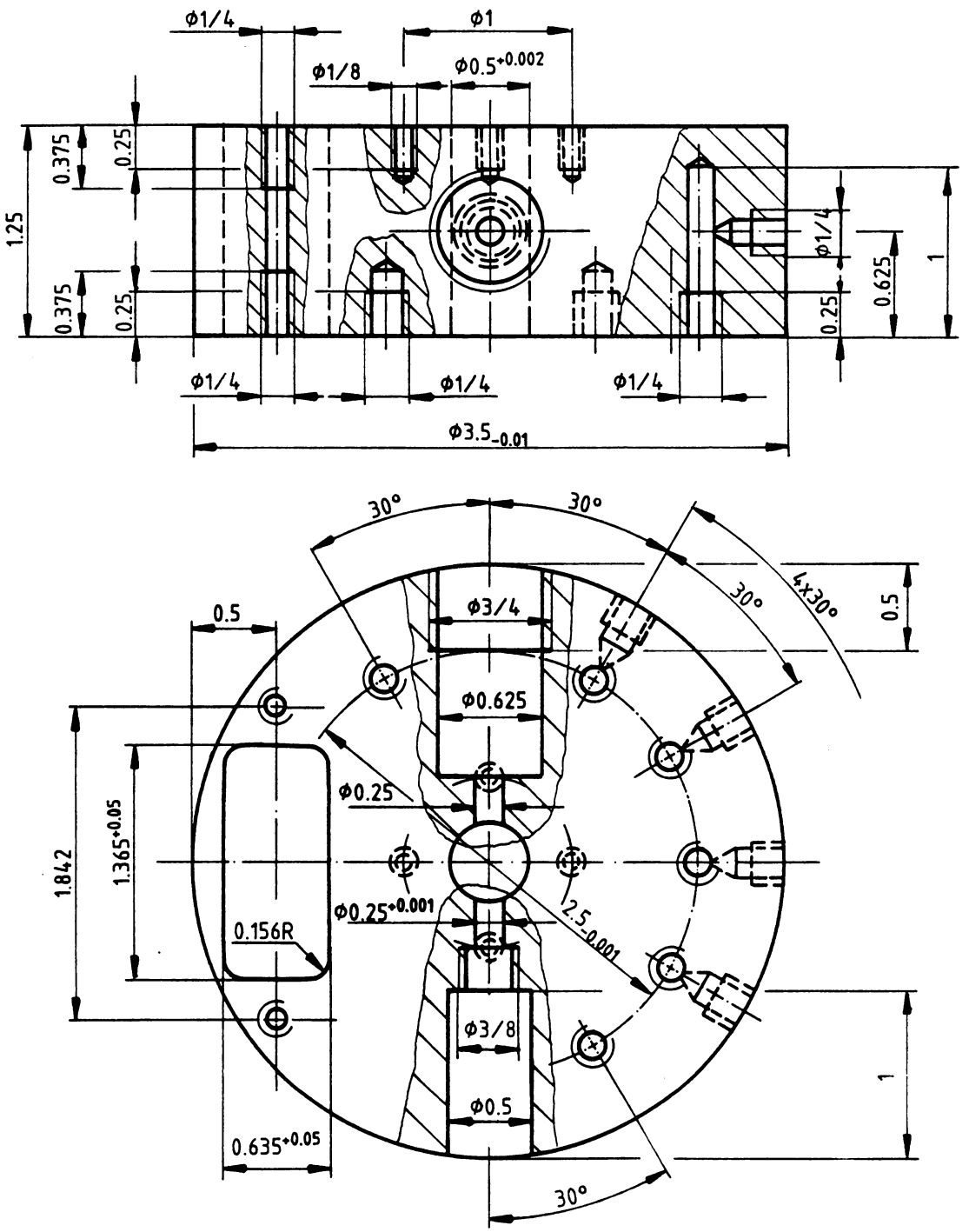




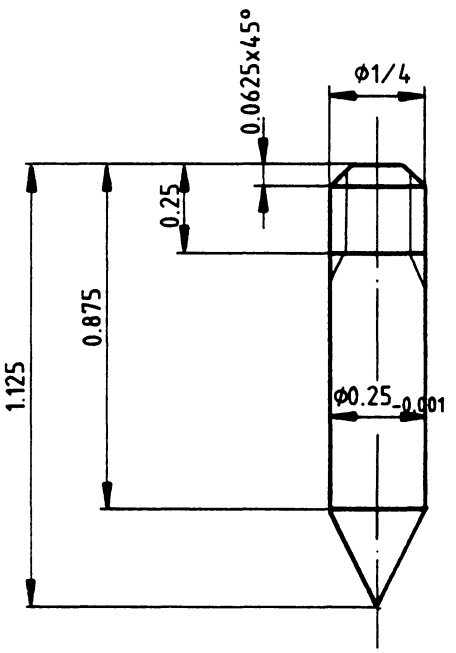
	Name	Date	Scale: 2:1	Material: Aluminum	
Work			Nut		No. 4
Check					



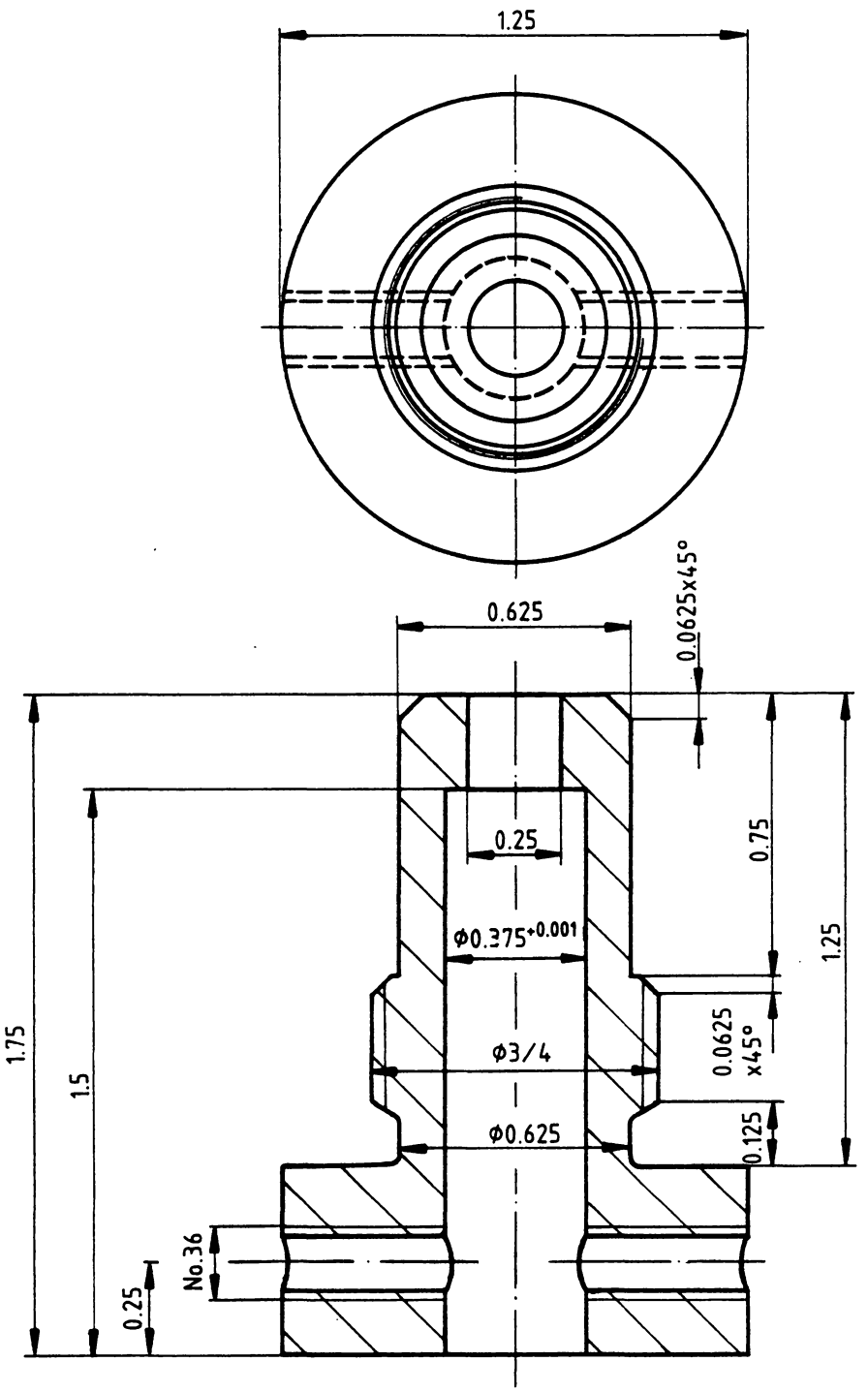
	Name	Date	Scale: 1:1	Material: Aluminum	
Work			Quick Change Lower Body		No. 1
Check					



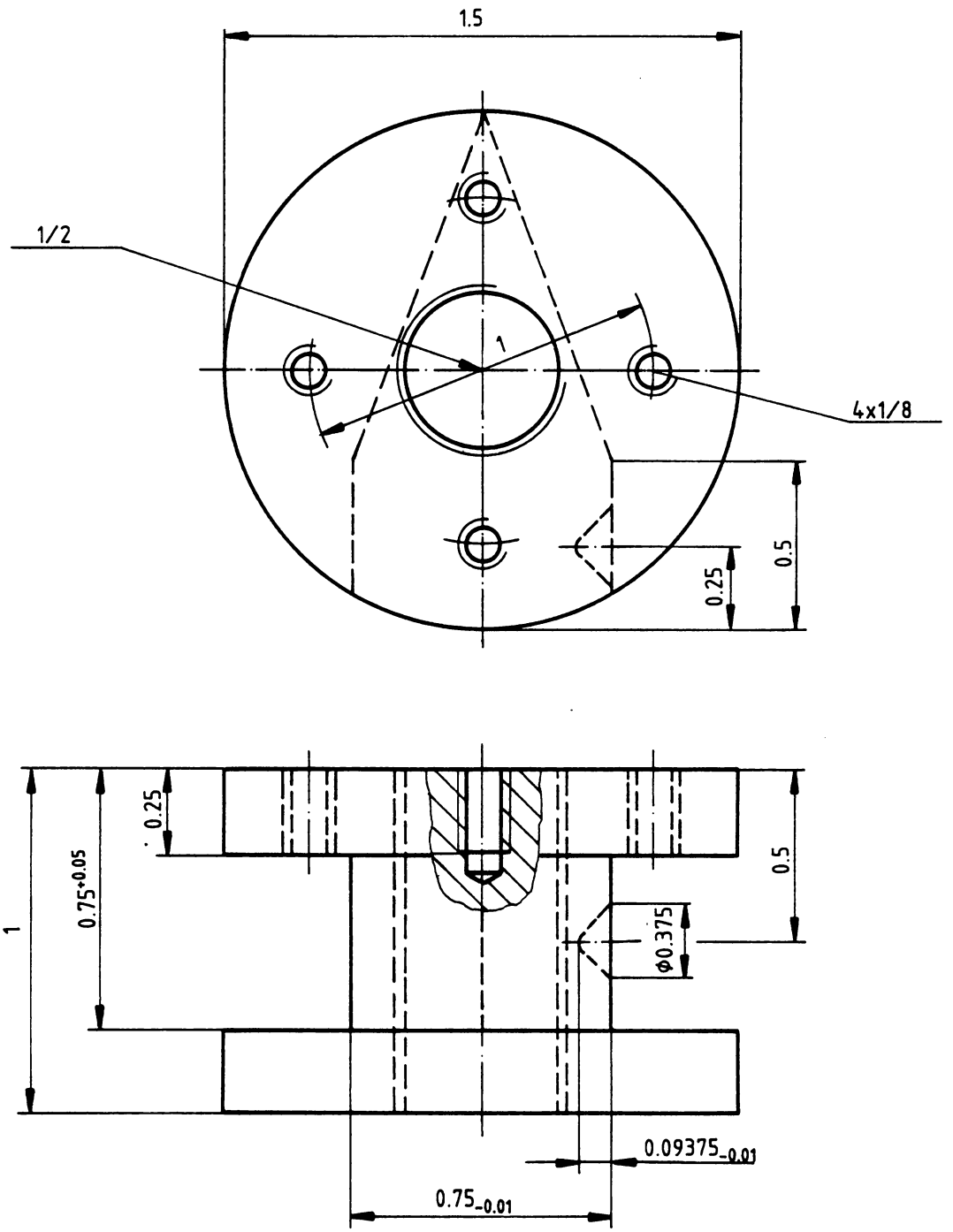
	Name	Date	Scale: 1:1	Material: Aluminum
Work			Quick Change Upper Body	No. 2
Check				



	Name	Date	Scale: 2:1	Material: Steel	
Work			Index Pin		No. 6
Check					



	Name	Date	Scale: 2:1	Material: Aluminum
Work			Cylinder Hull	No. 7
Check				



	Name	Date	Scale: 2:1	Material: Aluminum
Work			Face Plate	No. 8
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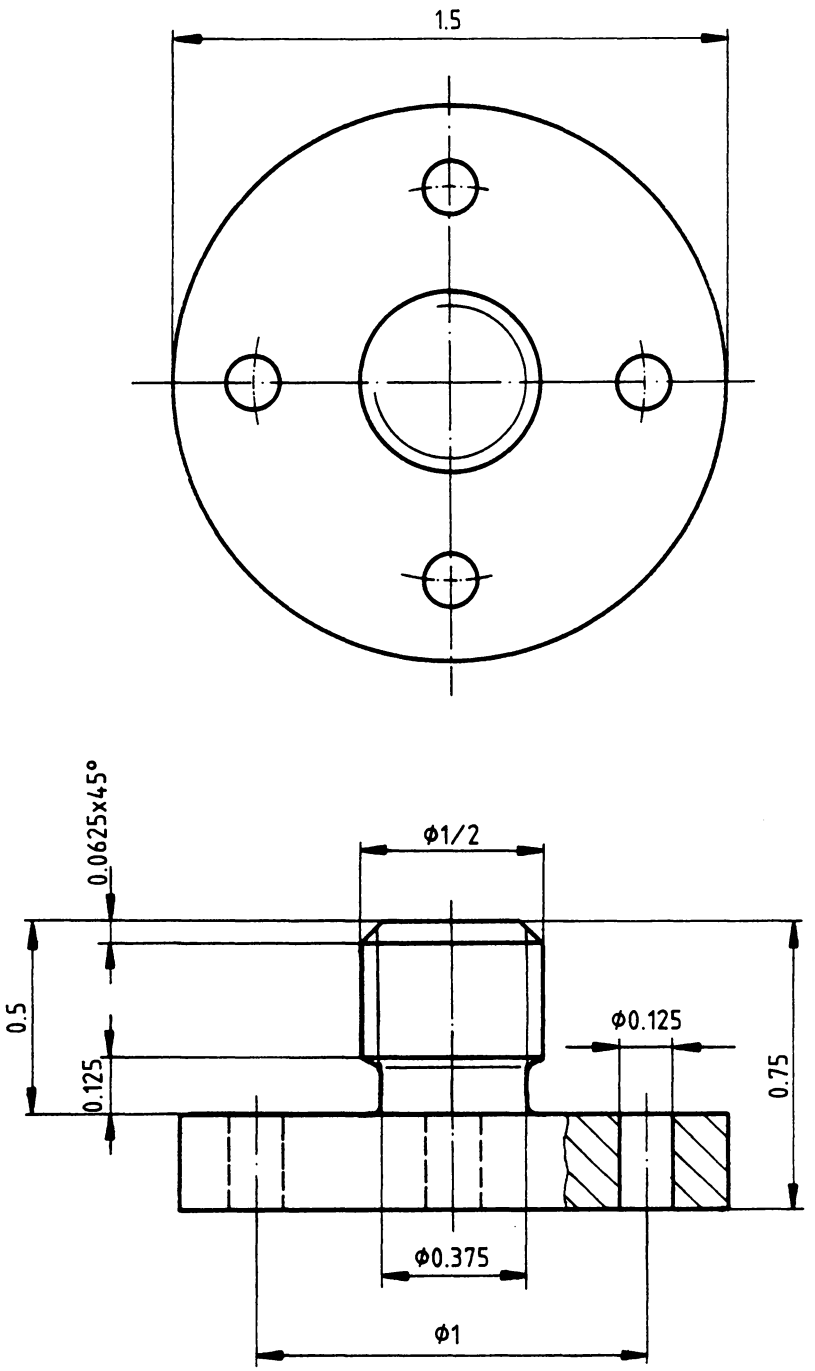
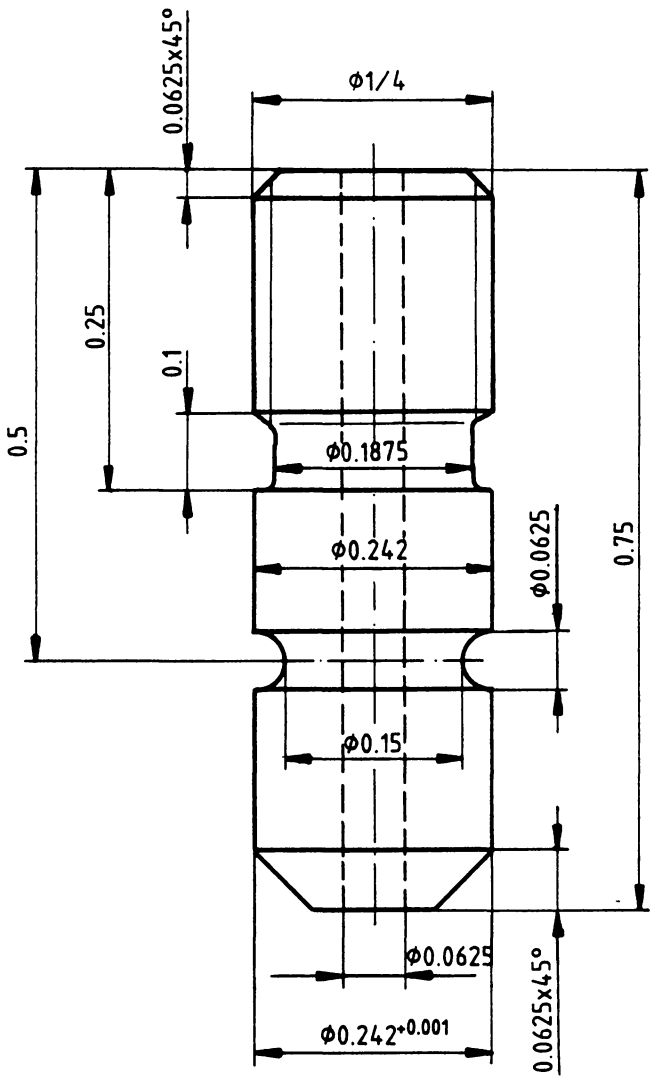
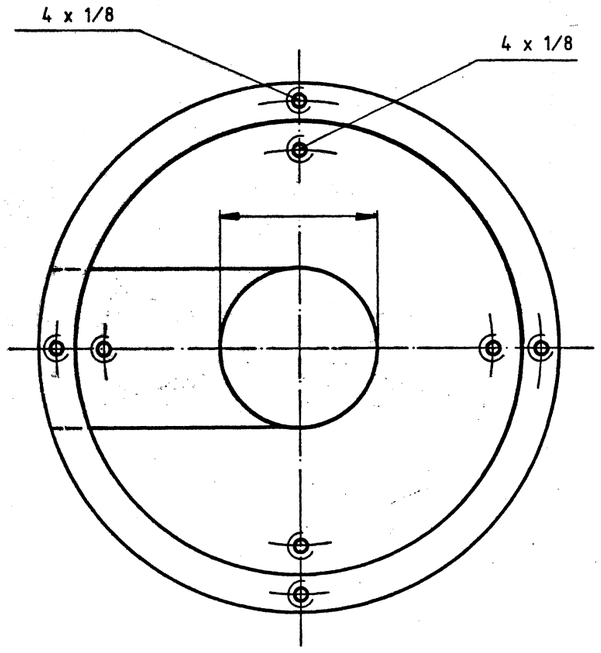
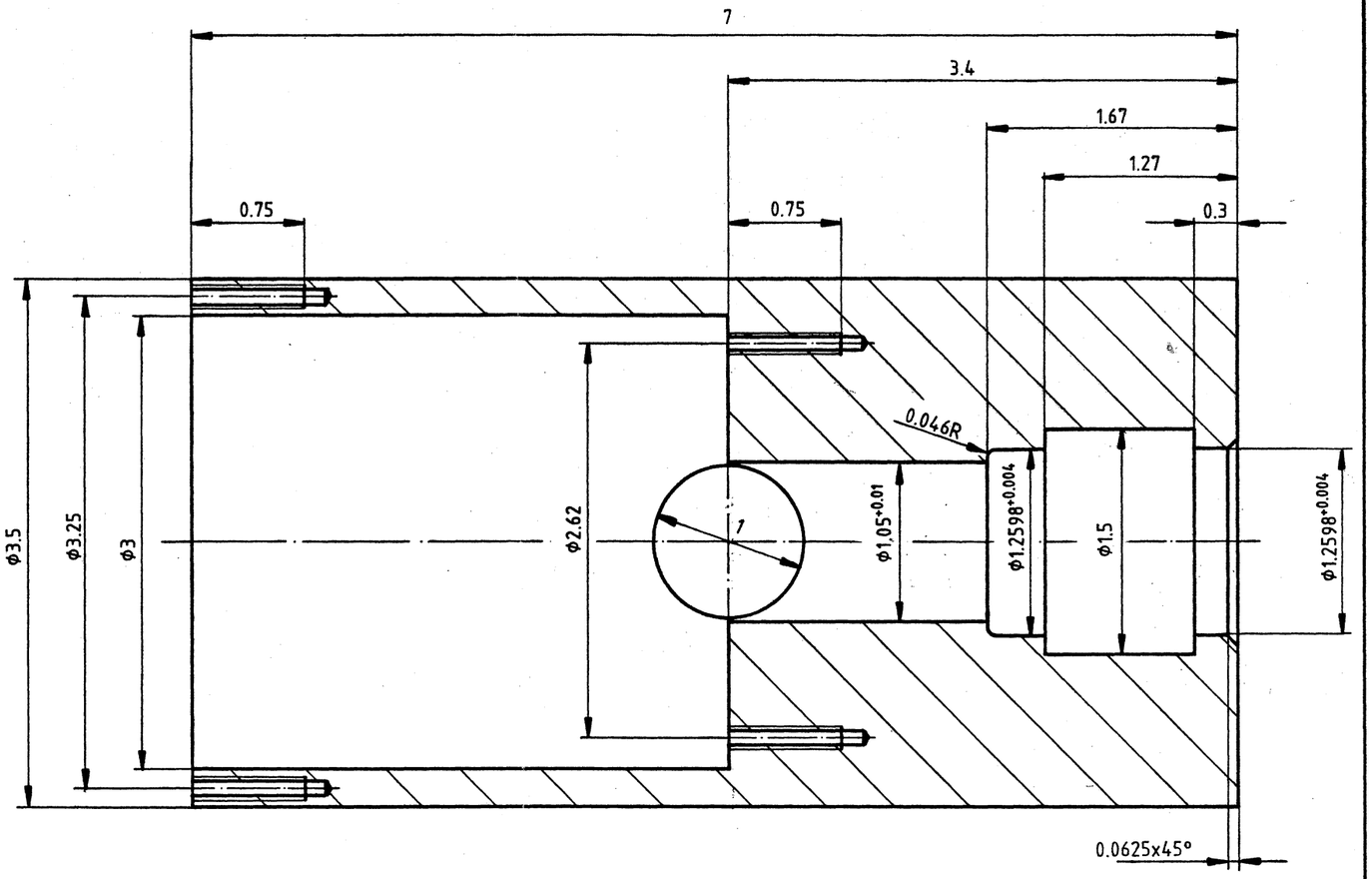


	Name	Date	Scale: 2:1	Material: Aluminum
Work			Mounting Plate	No. 9
Check				

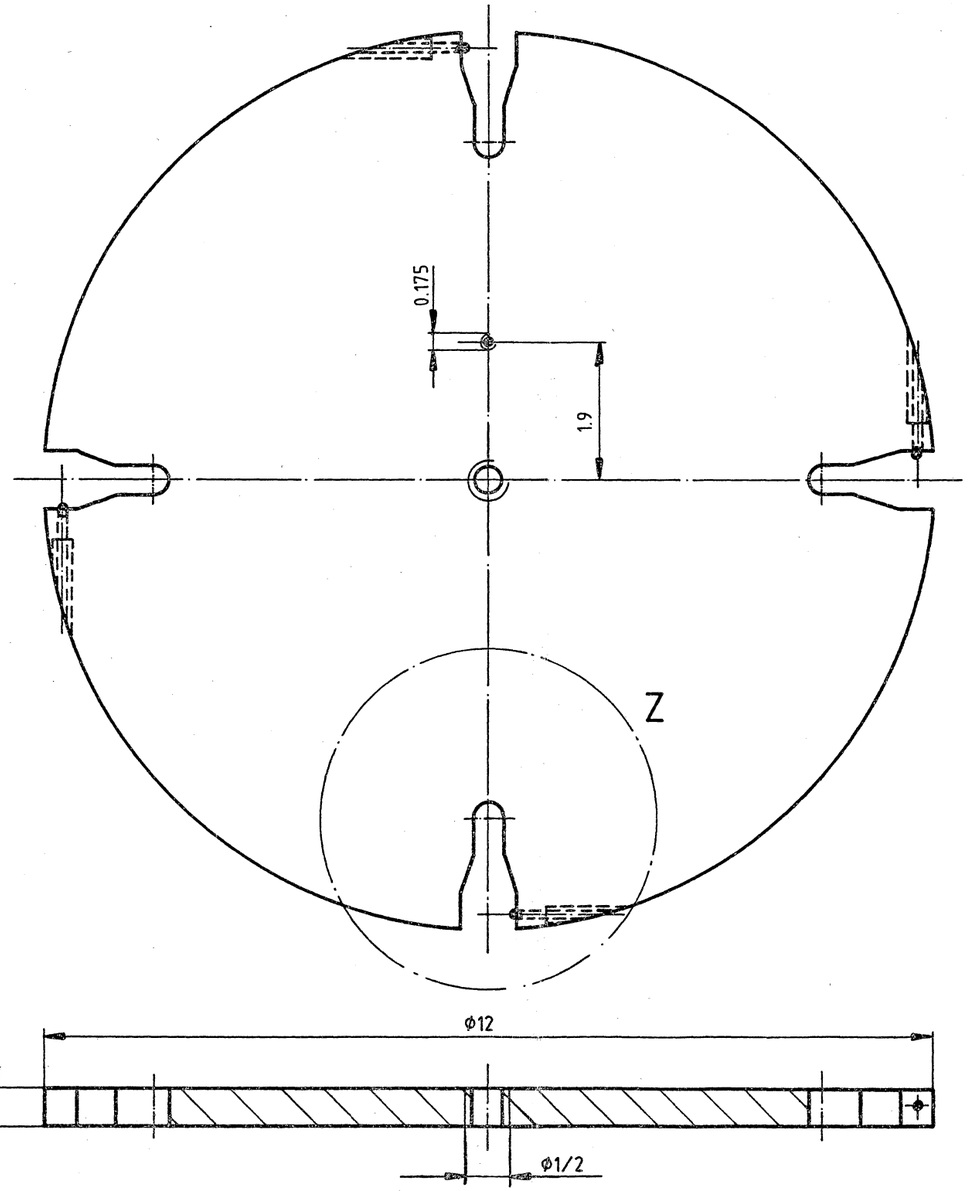


	Name	Date	Scale: 5:1	Material: Aluminum
Work			Nipple	No. 10
Check				



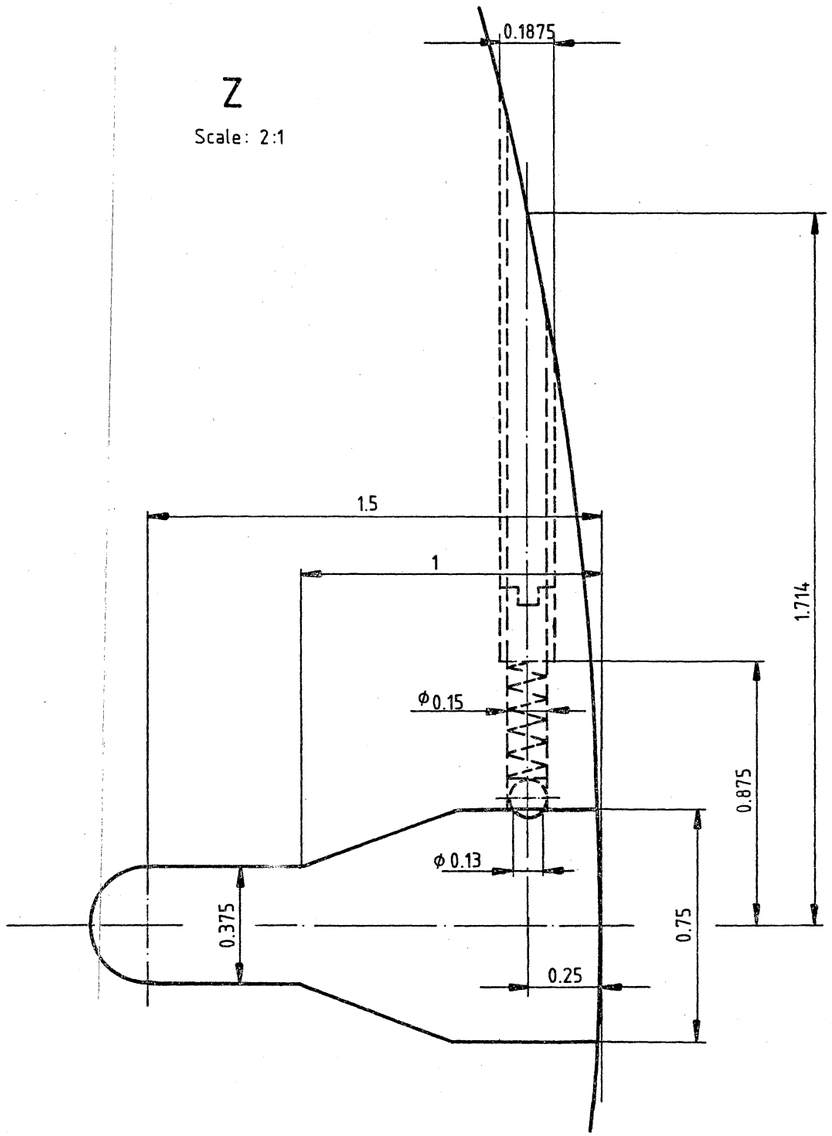


	Name	Date	Scale: 1:1	Material: Aluminum
Work			Body	No. 1
Check				

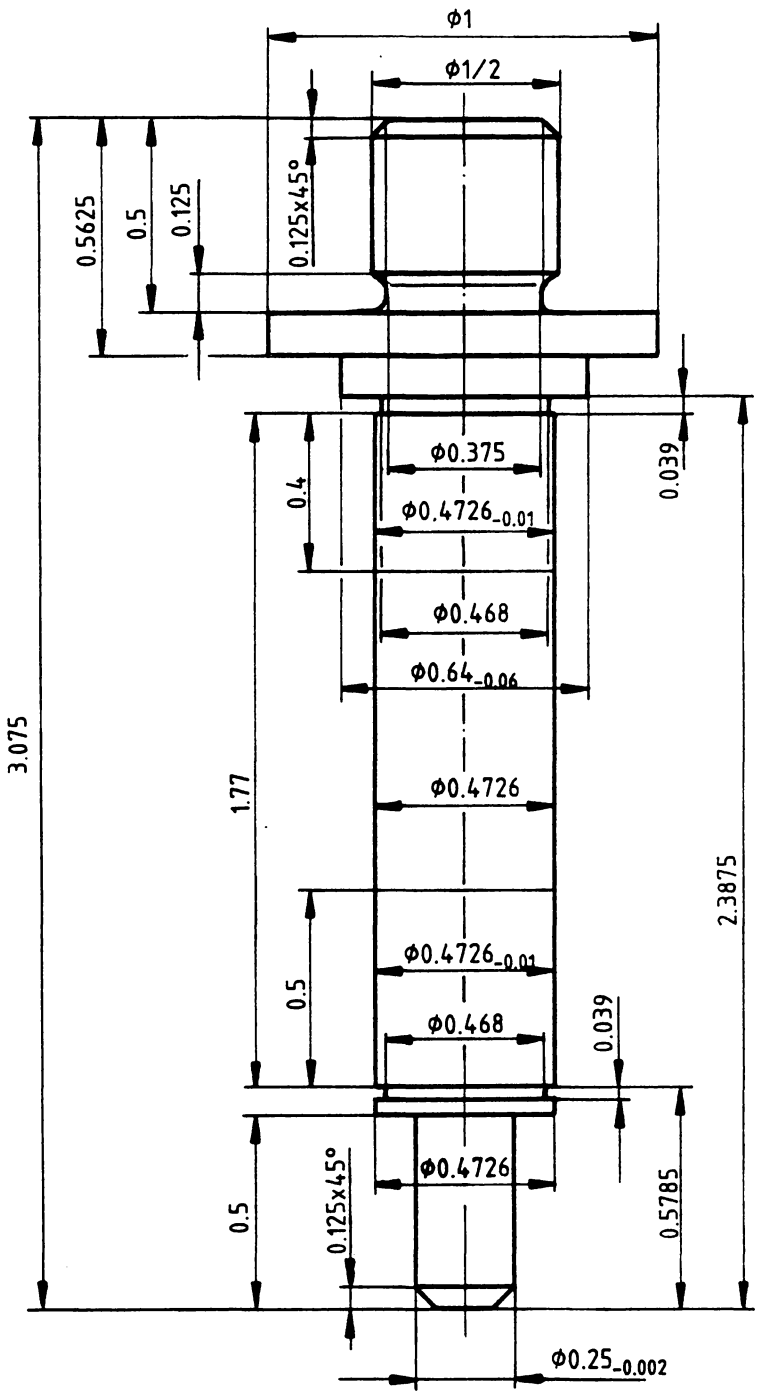


Z

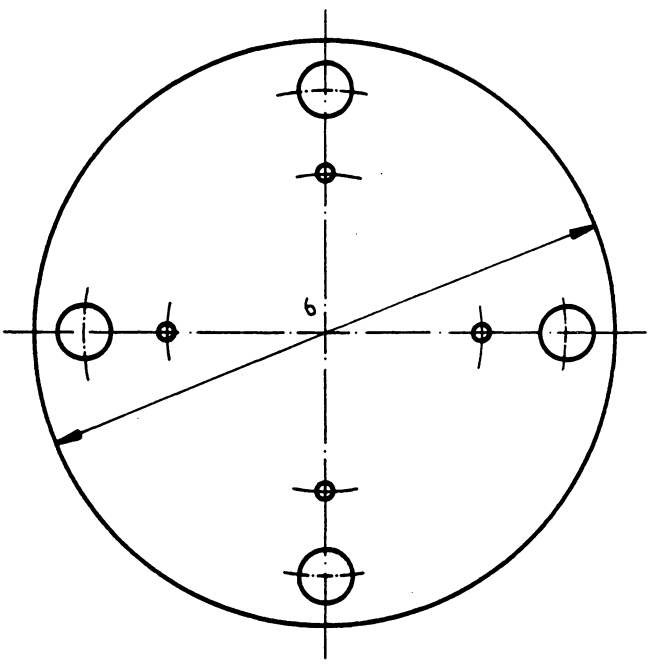
Scale: 2:1

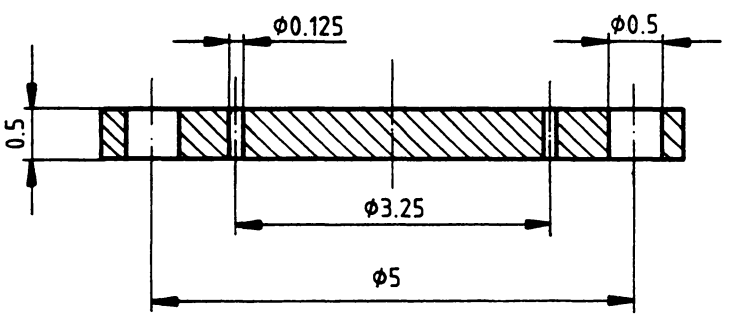


	Name	Date	Scale: 1:2	Material: Aluminum
Work			Turn Table	No. 2
Check				

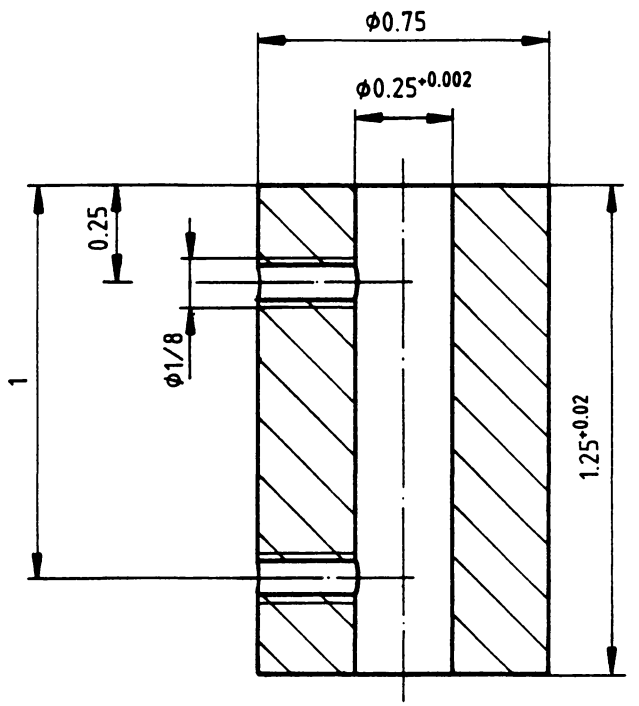


	Name	Date	Scale: 2:1	Material: Steel	
Work			Shaft		No. 3
Check					

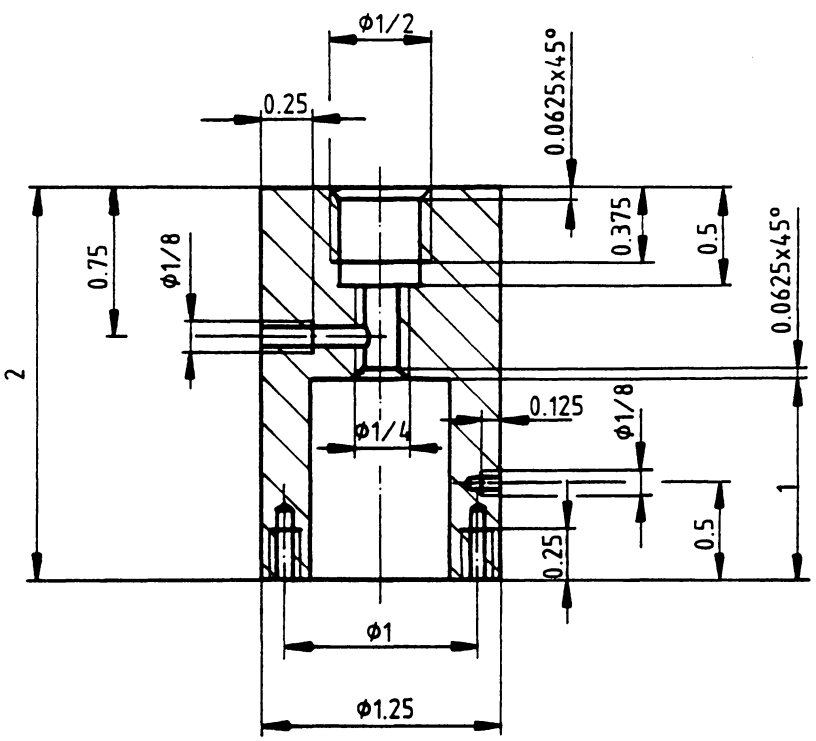


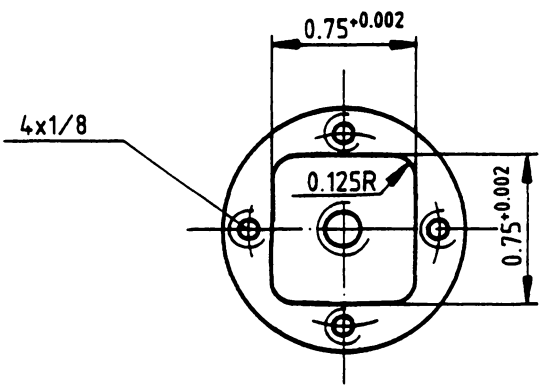


	Name	Date	Scale: 1:2	Material: Aluminum
Work			Bottom Plate	No. 4
Check				



	Name	Date	Scale: 2:1	Material: Brass	
Work			Coupler		No. 8
Check					





	Name	Date	Scale: 1:1	Material: Aluminum
Work			Body	No. 1
Check				

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