THE DESIGN AND PERFORMANCE OF A
SYSTEM FOR FLEXIBLE ASSEMBLY

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of the Requirements for the Degree
Master of Science

by
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CHAPTER I

SUMMARY OF ACCOMPLISHMENTS

The thrust of the work presented herein was to develop and test a robotic technique for flexible assembly. As a test of the technique, the specific task of assembling residential plumbing valves was undertaken.

A parallel jaw gripper used in the valve assembly process was designed to exhibit three features. The gripper jaws are sheathed with interchangeable gripping surfaces so that an assortment of gripping surfaces are available to enable the robot to grasp all parts composing the product assembly. The gripping force of the gripper is digitally controlled by a mainframe computer which does so by monitoring the driving motor torque. To enable programmable tool exchange, the gripper is designed to be both parkable and attachable. The gripper was the main element of flexibility in the development of the assembly system.

A methodology for feeding, handling, and assembling difficult part shapes was developed. Once the assembly procedure was ascertained, feeders and escapements were then designed to achieve part orientations and locations dictated by manipulator handling tasks. Most of the parts were fed by devices which were simple in operation because part shape and mass distribution were amenable to simplistic methods of feeding. But a few parts were cumbersome in
finished form and conveying them required the development of special feeding apparatus.

A system for controlling the assembly process was developed. This involved the integration of electrical and pneumatic devices utilizing analog and digital sensing, and the development of a method of interfacing the robot controller with a computer which was capable of analog data acquisition.

To control work station peripherals such as feeders, programs were written in both VAL and FORTRAN languages. Control is divided into two phases. The mainframe computer provides monitoring of the controlled variables by using FORTRAN algorithms. The robot controller accomplishes the switching function of control according to VAL code. The computer and controller are hardware and software interfaced to provide communication to implement the two phase control strategy.
CHAPTER II

INTRODUCTION

Generally, hard automated assembly systems are sensitive to product changes in that redesign and capital replacement of machinery may be necessary to accommodate product changes. Since robot controllers can be reprogrammed, robotic assembly systems are less sensitive to product change when compared to hard automated systems. Hence a robotic manipulator imparts a degree of flexibility to an assembly process. The purpose of the thesis research presented herein was to develop a system of flexible assembly.

In searching the literature, no single definition of the term flexibility was found to be universally accepted in the context of flexible manufacturing systems. For purposes of discussion herein, flexibility will be that characteristic of an assembly process which is an indicator for the process to accept changes by forces internal and external to that process. An external force could be dimensional changes of product components from one batch to another while an internal force could be wear of the machine cutting tool. Several techniques for imparting flexibility to manufacturing systems which utilize a robotic manipulator were reviewed.

Consider an assembly process fed parts such that the parts do not always arrive at a robotic work station in the order in which they would be assembled or when they are needed. For example, consider an
assembly W which is composed of subassemblies X and Y. Subassembly X is composed of A, B, C and D where part B is installed upon A followed by either parts C or D. Subassembly Y is assembled from parts E and F in that order. Finally, subassembly Y is installed upon X to form assembly W. The programmer of the robotic manipulator has programmed the controller to accept and assemble the parts in the order A, B, C, D, E and F. If parts C through F have been delivered, the assembly process is stalled until parts A and B arrive. There is no physical constraint preventing the assembly of parts E and F to form subassembly Y, since they have been delivered. Fox and Ho [1] have developed an algorithm using Pascal. With the algorithm implemented, the manipulator temporarily stores the delivered parts which cannot be assembled and assembles those which can be assembled. Hence, the assembly process has been rendered flexible to randomness in the order of parts feeding.

Often in assembly and manufacturing processes, parts have to be placed in holding fixtures prior to performing operations involving them. In batch operations where the basic product design is maintained and the component part dimensions are changed between batches, the cost of fabricating and changing rigid fixtures to accommodate batch differences could be reduced or eliminated if flexible fixtures were developed. Asada and By [2] have developed a technique for automatic workpart fixturing for flexible assembly. The technique is applied through a computer-aided design (CAD) system which includes a manipulator, a fixture assortment, and a magnetic
chuck for the fixtures. The computer determines which fixtures and their locations on the magnetic chuck are necessary to constrain the workpart based upon the problem geometry. The manipulator then picks from the fixture assortment and places the fixtures upon the magnetic chuck to establish fixturing for the workpart.

Sometimes complicated workpiece geometries are responsible for significant expenditures for the cost associated with fixturing workpieces during manufacture by multiple machining processes. The proposed solution is of interest here since the method could be extended to an assembly process requiring multiple fixturing or involving part size variation between batches. Wright and Cutkosky [3] proposed a programmable clamping system for such workpieces. The system consists of a configurable clamp adjusted to fit the work piece by computer control using part geometry information stored in a CAD data base. The clamp then travels with the workpiece from fixture to fixture. A clamp for turbine blades has been explored for use during blade manufacture. These two techniques have potential for making fixturing for assembly flexible.

Some fabrication processes such as welding can cause dimensional errors in the finished part. Consider a shaft and matching flange which is composed of a bored boss welded to an annular plate. After the flange is fixtured, the shaft and flange bore center lines may have to be aligned prior to shaft insertion. Artigue and Francois [4] have developed a process of reference searching and position
adjustment before insertion which is based on an end effector which resembles a lens turret for a microscope. For the case considered, the workpiece gripper and a reference searching transducer are mounted to the base plate of the end effector such that they are mounted radially equidistant from the center of the robot wrist flange and 180-degrees apart. The reference transducer is used to determine the location of the flange bore. The shaft is then inserted using a correction based on input data from the displacement transducer. Therefore, the assembly process is flexible to the tolerances which result from welding.

Flexibility in manufacturing systems with respect to parts handling can be attained through robotic end effector design. Luo [5] has been developing a parallel jaw gripper which utilizes uniaxial slip sensors mounted orthogonally on the fingers. That researcher suggests that the slip sensors be used in an adaptive control scheme for the gripping force because variation in workpiece size and weight are common in material handling processes. Wright [6] has developed an end effector exchange mechanism which allows the automatic change of tools. That author suggests that the tool exchange mechanism increases work station flexibility by increasing robot versatility. The flexibility of the assembly system to be discussed is accomplished mainly through end effector design.

In the present study an end effector design based on a parallel jaw type of gripper was developed. A schematic of the final end
effector design which was used in the assembly system is shown in Fig. 2.1. There are three features of the resulting gripper design which act to improve flexibility of an assembly process. First, the gripper jaws are sheathed by a pair of aluminum sleeves which can be removed and replaced by other pairs of sleeves without human intervention. A sleeve pair can be machined or modified to conform to part configurations during grasping tasks. Therefore, if a plant engineer has to make changes in an assembly process to compensate for component part redesign, the engineer need only order the fabrication or modification of a sleeve pair.

The second gripper feature of importance is that of detachability. The wrist flange of the laboratory robot (6-degrees of freedom, PUMA 560 industrial robot) is fitted with a pneumatic adapter to permit programmed tool change. The adapter, as shown in Fig. 2.2, possesses the female electrical power, electric signal and pneumatic connectors necessary to mate with tools with matching male attachments. Therefore, end effectors can be readily interchanged to suit different assembly tasks. The parallel jaw gripper is designed to be detachable from the adapter.

The third gripper feature has to do with gripping force control. An Intel 310A computer was used to monitor the motor current through an analog to digital converter. After a set point is reached or surpassed, a TTL signal (from a parallel input/output board) is used to signal the PUMA controller to switch off power to the motor.
Figure 2.1. Schematic of Adapter, Gripper, and Jaw Sleeves.
Device Identification:

1  Pneumatic Gripper
2  Parking Station for Exchangeable Gripping Surfaces or Gripper
3  Gripper
4  Pneumatic Adapter.

Figure 2.2. Pneumatic Adapter.
The task of developing flexible assembly techniques for the assembly of standard water valves was undertaken. The valves chosen were Nibco 1/2-inch globe valves shown in Fig. 2.3. These valves are used in residential plumbing systems where solder joints are prominent. A valve was chosen as the product to be assembled since it satisfies four important criteria:

First, the product demand had to be of a level to make robotic assembly economically justifiable when compared to assembly by manual labor. Nibco assembles valves by hand, and considering the great dependency of the housing construction industry on such a product, robotic assembly might prove attractive to valve manufacturers.

Second, the product had to be available in a range of sizes which requires the flexibility imparted by a robotic work station. A given design of valve is commercially available in a variety of sizes as supplied from a manufacturer.

Third, the product had to be designed for assembly. According to Riley [7], parts of an assembly should ideally be inserted from one direction to facilitate mechanized assembly. If one views the disassembled valve in Fig. 2.3, it is evident that the valve is a uniaxial assembly.

Fourth, the product assembly had to involve close fit
Valve Part Identification:

1 Gasket  4 Packing Adjustment Nut
2 Bonnet  5 Phillips Head Screw
3 Stem  6 Body
7 Handle

Figure 2.3. Nibco 1/2-inch Globe Valve.
insertion tasks. The Nibco valve chosen requires insertion processes with diametral clearances on the order of a few mils. Methods of economically feeding component parts are employed.

A conveyor, transfers and escapements for feeding the valve parts to the robot work station were designed so as to provide an affordable simulation of commercially available parts feeding equipment. An oval, model-railroad layout is used to resemble a conveyor belt. Chute type transfers which utilize gravity feed and a pneumatically controlled rotary table feeder were used in lieu of vibratory bowl feeders.
CHAPTER III
DESIGN OF THE GRIPPER

During the course of end effector design and fabrication, many requirements were placed upon the design and then relaxed later. Only those requirements which were satisfied by the final gripper form will be considered herein.

At the outset of gripper design, the staff of the Department of Mechanical Engineering decided to use an electric motor driven lead screw to open and close the jaws of the parallel jaw gripper. The parallel jaw gripper design had to be structurally rigid, low in mass, and inexpensive to fabricate. The end effector had to be structurally rigid and light because of the following specifications. First, the finished gripper weight could not appreciably reduce the payload capacity of the robot. Second, the gripper had to be capable of applying grasping force controllable in the range of 0 to 15-pounds. Third, the free end deflection of either cantilevered jaw finger during grasping had to be minimized to approximately 0.010-inch to insure positioning repeatability of grasped parts. The moment, shear and thrust reactions which are induced by both grasping and moving a heavy object have to be resisted by the gripper structure. Since the working stress levels were anticipated to be low, aluminum alloy was chosen for the basic structure because it is inexpensive, easily worked, and light. Bronze bushings and brass nuts were used to transmit the reaction load to the base structure which consisted of
two bearing blocks and a channel-type base plate as shown in Figs. 3.1 through 3.3. The lead screw and alignment bar are made from steel for wear compatibility with the bearing metals (see the appendices for component part drawings).

Provisions were made during synthesis such that the resulting gripper design could accommodate additional sensory transducers and be an interchangeable tool with respect to the robot wrist adapter. The Delrin stock from which the jaws were made provided strength and lightness, as well as sufficient stock for the later addition of an emitter-detector pair or an air jet sensor. To make the gripper adaptable to the robot wrist, a male mate was fabricated from the drawing shown in Fig. 3.4 and mounted as pictured in Fig. 2.2. Having outlined the constraints and expectations placed upon the design, the design procedure for the gripper will be reviewed.

The lead screw and gear train were designed to produce up to a 15-pound grasping force at the jaws of the parallel jaw gripper. The emphasis on design of power transmission components to achieve the grasp specification was due to the use of an available 24-Volt DC motor. Several lead screws and gear train combinations were analyzed, but the design analysis which was applied to each combination is demonstrated herein for the final choice only.
Figure 3.1: Plan Drawing of Gripper.
Figure 3.2. Front View Drawing of Gripper.
Figure 3.3. Side View Drawing of Gripper.
Figure 3.4. Adapter Mounting Provision for Gripper.
Gripper Mechanical Design

The first step in the analysis is to consider the torque required on the lead screw to produce the 15-pound gripping force at the jaws. Since the drive motor was specified, different thread specifications were tried in the analysis to best utilize the motor. According to Shigley [8], the following equation is used for computing the torque required to move a load via a power screw is:

\[
T = F \times D_m \times (L + \pi \times U \times D_m \times \text{sec of } B/2) / (2 \times (\pi \times D_m - U \times L \times \text{sec of } B/2))
\]  

(3.1)

where:  
\(T\) is the driving torque (inch-pound-force)  
\(F\) is the gripping force (pound-force)  
\(D_m\) is the average diameter (inch)  
\(L\) is the screw lead (inch of travel/turn)  
\(\pi\) is 3.14159...  
\(U\) is the coefficient of friction for thread surface contact  
\(B\) is the thread angle as shown in Fig. 3.5 (degree).

The average diameter was taken as the basic pitch diameter as defined by Baumeister and Marks [9].

\[
D_m = D - (L/2)
\]  

(3.2)

where \(D\) is the major thread diameter (inch).
Figure 3.5. Thread Angle, B.
For a major thread diameter of 5/16-inch and 18 UNC thread,

\[ D_m = \frac{5}{16} - \left(\frac{1}{18}/2\right) = 0.2847 \text{ in.} \]

and

\[ T = 15 \times 0.2847 \times \left(\frac{1}{18} + 3.14159 \times 0.44 \times 0.2847 \times \text{sec of 60}/2\right)/ \]
\[ (2 \times (3.14159 \times 0.2847 - 0.44/18 \times \text{sec of 60}/2)) \]

\[ T = 1.26 \text{ in.-lb.} \]

where: 0.44 is the kinetic coefficient of friction for the steel lead screw acting on the brass nuts which are pressed into the Delrin jaws.

By Newton's law of equal and opposite reactions, each jaw is loaded with 15-pounds. Therefore, the required torque is twice that computed since the lead screw has left hand thread on half its length and right hand thread on the other, for opposed jaw operation. So,

\[ T = 2.52 \text{ in.-lb. (40.3 in.-oz.)} \]

To avoid the use of spur gears which would require custom manufacturing, matched pinion and driven gear sets were selected from among manufacturers' cataloged inventories. According to Baumeister and Marks [9], the minimum number of drive pinion teeth is 18 for a
diametral pitch of 48/inch. The final assembly utilizes a 28-tooth motor pinion and 186-tooth driven gear. The gears are cut from 3/16-inch thick Delrin stock. Therefore, the motor torque required to produce 15-pounds of gripping force is

\[ T_m = \frac{40.3}{186/28} \text{ in.-oz.} = 6.1 \text{ in.-oz.} \]

which is a 34% utilization of the measured motor stall torque of 18 in.-oz. During gripping force tests, a gripping force value of 15-pounds was obtained when the drive motor was stalled (see calibration curve for compression spring in appendix). Hence, the motor provides adequate compensation for unpredictable friction losses. A side benefit is that the jaw velocity is kept high so that time is not wasted during assembly in the positioning of the gripper jaws. The measured stall torque is used next to determine the safety factor on the gear tooth bending stress.

According to Shigley [8], the tooth bending stress is defined by

\[ S = \frac{W_t \cdot P}{(F \cdot Y)} \quad (3.3) \]

where:  
- \( S \) is the tooth bending stress (pounds per square inch)
- \( W_t \) is the tooth load (pounds)
- \( P \) is the diametral pitch (1/inch)
- \( F \) is the tooth face width (inch)
- \( Y \) is the form factor tabulated by Shigley [8] for a 20-degree
The diametral pitch of the pinion gear is 48/inch and the tooth bending stress neglecting load sharing is

\[ S = (2 \times \frac{T_m}{28}) \times \frac{P}{(F \times Y)} \]
\[ = (2 \times \frac{18}{16} \times 48/28) \times 48/[(3/16) \times 0.353] \]
\[ S = 2800 \text{ lb./sq. in.} \]

The maximum shear stress theory (Coulomb theory) of ductile failure is applied to determine factors of safety with failure occurring by yielding. From a design handbook [10], the yield stress for Delrin is 10,000-pounds per square inch which results in a safety factor of 3.57 for the pinion gear. Similarly, for the driven gear,

\[ S = (2 \times \frac{18}{16} \times 48/28) \times 48/[(3/16) \times 0.463] \]
\[ S = 2140 \text{ lb./sq. in.} \]

The safety factor for the driven gear is 4.67. Next the analysis leading to the determination of the section property of the Delrin jaws is considered (The results of analyzing a gear train of greater ratio is in the appendix.).

The criteria for choosing a jaw section modulus was the limitation of the transverse free end deflection of either jaw to 0.010-inch for a worst case load of 15-pounds. The worst case load is
a 15-pound grip reaction applied to the free end of a cantilevered jaw finger as shown in Fig. 3.6. From Shigley's design text [8] for elastic deformation of a cantilevered beam,

\[ Y_{\text{max}} = \frac{4 \times F \times L^3}{E \times a^4} \]  

(3.4)

where:  
\( Y_{\text{max}} \) is the maximum beam deflection (inch)  
\( F \) is the applied transverse load (pound)  
\( L \) is the beam span (inch)  
\( E \) is the modulus of elasticity (pound/square inch)  
\( a \) is the square section width (inch).

For the 3/4-inch wide square section and an elastic modulus of 410,000-pounds per square inch which was taken from property data provided by the supplier of the Delrin,

\[ Y_{\text{max}} = \frac{4 \times 15 \times 3^3}{(410,000 \times 0.75^4)} \]

\[ Y_{\text{max}} = 0.013-\text{in.} \]

The above result appears to indicate a borderline design choice if the 10-mil specification is applied as a limit. But, the interchangeable jaw sleeves to be discussed sheathe the cantilevered section of each jaw when the gripper is in service. Therefore, the maximum deflection of a jaw is less than computed because of the additional rigidity imparted by the aluminum sleeves.
Figure 3.6. Cantilever Model of a Delrin Jaw.
The interchangeable jaw sleeves as shown mounted in Fig. 3.7a, were the result of attempting to satisfy three design requirements by trial and error. First, gripping surfaces which could be removed or attached to the gripper jaws without human intervention were required. Second, the gripping surfaces and the mechanical means for retaining or detaching them could not interfere with the gripping force sensory transducer and the wiring necessary for transmission of transducer output. Third, the gripping surfaces could not prevent the future installation of plumbing for an air jet sensor by masking jaw surface which would have to be available for that installation. In the interest of reader understanding of the last requirement, a brief discussion of the air jet sensing method will be presented.

An air jet sensor allows the presence of an obstacle to be detected. A typical design, as shown in Fig. 3.8, consists of an air pressure source feeding a restriction at the entrance to a closed channel which is connected to a nozzle. A static pressure tap, which is located between the restriction and the nozzle, indicates the presence of a flow obstruction in the jet stream exiting the nozzle when the obstruction causes a pressure increase. According to Belforte, D'Alfio, Quagliotti, and Romiti [11], a counter-pressure sensor must be sized so that the sensor responds with a large step change at the static pressure tap to actuate a pneumatic relay when an obstacle is placed a known distance from the nozzle exit. If the sensor is being used to stop obstacle motion toward the sensing element, that known distance must be sufficient to allow time for
Figure 3.7a. Tool Adapter and Parallel Jaw Gripper.
Figure 3.8. Air Jet Sensor Schematic.

Nomenclature:  
- $P_s$ - Supply Pressure  
- $P_T$ - Tap Static Pressure  
- $D$ - Obstacle Distance from Nozzle Exit.
relay switching prior to cessation of obstacle motion.

If for example an air jet sensor is installed on the gripper in Fig. 3.7a for sensing an obstacle presence at the free end of a jaw, a blind hole would first have to be drilled concentrical with respect to the jaw centerline. To finish forming the sensor channel, a second hole would have to be cross drilled to meet the end of the first by entering between the lead screw and jaw sleeve opposite the sleeve retaining detent. Since the normal stress is zero along the neutral axis of a section of a beam in bending, the channel is so located to minimize the effects of both normal stress concentration and section modulus reduction.

An interchangeable gripping surface mounted to a pressure sensing bellows for monitoring the force of grip was experimented with. Several bellows were formed by caulking a rectangular pair of 20-gauge steel plates together with a water soluble core. The fabricated units failed during bench testing and further development of the method was abandoned in favor of the method which was ultimately employed.

The jaw sleeves shown in Fig. 3.7a are a slip fit onto the jaws, and they are retained by a detent which utilizes a spring-loaded plunger. The spring-loaded plunger is mounted between the jaw alignment bar and lead screw on each jaw. Referring to Fig. 2.2, there is a pin for each slot of the tool-parking station which depresses the plunger of the detent as the lands of a jaw sleeve
engage the slot. These lands are visible in Fig. 3.7a and shown in
the drawing of Fig. 3.7b. When the sleeves are against the vertical
flange of the slotted angle, the plungers are fully depressed. At
this point, the gripper jaws can be slid from the sleeves. The
commercially available plunger assembly was chosen when a leaf spring-
type detent failed to function properly (see the appendix for the
alternate detent drawing). Since the gripping force is transmitted
through the gripping surfaces to the jaws, the choice of method for
sensing grip magnitude is influenced by the design of the gripping
surfaces as discussed later.

Gripping Force Sensing

The methods of force sensing reviewed fall into two classes. First, there are those which sense the force of grip directly and
those are a carbon fiber tactile sensor, a conductive silicone rubber
transducer, and a bellows-type transducer. Second, there are methods
which sense the gripping force indirectly and they are drive motor
torque measurement and jaw surface strain measurement. The methods
just noted will be surveyed sequentially with emphasis on the method
employed.

If a gripping surface which covers only the inner and outer jaw
surfaces had been employed, tactile force sensors could have been
inexpensively applied using carbon fiber felt. The simplest form of
such a sensor is a piece of carbon fiber felt sandwiched between a
Figure 3.7b. Gripper Jaw Sleeve Drawing.
pair of metal foil electrodes. The resistance of the sensor decreases when the applied load increases because the area of inter-fiber contact created by the multiple fiber substructure of the felt increases. According to Larcombe [12], the inherent sensor noise at low loads is caused by the sensitivity of individual fiber junctions to environmental vibration. That author indicated that the junction noise could be reduced by placing the sensor in a state of initial compression and by using felt which has a high fiber count. In tests using a sandwich of two fiber ribbon sections which produced a cross section of 5 by 0.1-millimeters and a no load resistance of 2000-ohms, Larcombe [12] was able to apply a pressure of up to 4000-kilograms per square centimeter (56,900-pounds per square inch) at which point the material exhibited signs of distress. That sensor displayed a dynamic range of at least four decades of resistance with disregard for the initial compression stage.

Another force transducer from the same category utilizes conductive silicone rubber. Purbrick [13] found that by crossing a convex cord of conductive silicone with a flat electrode and grounding one end of the silicone cord, a resistive junction was produced, which increases in resistance as it is compressed. That author monitored the voltage response of the junction to increasing load while the junction was connected in series with a 1000-ohm ballast resistor and a 5-Volt DC supply. He found the output to be useable up to a load of 10-kilograms per centimeter of cord length with no detectable damage to the transducer.
When the jaw sleeve design shown in Fig. 3.7a was chosen, the risk of shear damage to the force sensor during sleeve change precluded the use of all sensors described in the direct sensing category.

The gripping force can be sensed indirectly by measuring the Delrin jaw surface strain with resistance-type strain gages. Wang and Will [14] developed a gripping force sensor based on bonded strain gages for computer controlled mechanical assembly. Their force sensor was protected with overload stops to limit the maximum force to 1500 grams. That sensor consisted of two pairs of strain gages which formed the four legs of a Wheatstone bridge. One gage of each pair responded to maximum compressive strain and the other to maximum tensile strain induced by bending. Both gage pairs were mounted to the same gripper jaw. The method employed by those authors had to be modified when the decision was made to utilize the full length of the jaw inner surfaces for grasping.

To prevent damaging gages when gripping close to the lead screw, the measurement scheme considered would receive only compressive strain signals from two gages mounted on the outside of a jaw at locations $X_1$ and $X_m$ in Fig. 3.9. The following analysis ultimately relates the compressive strain measured at those locations directly to the force by application of flexure and bending theory. To begin the analysis, the reader will recall the following equality from strength of materials (refer to Fig. 3.9).
Figure 3.9. Cantilever Model of Jaw Finger.
The resistance strain gages are in compression on the bottom side
of the jaw model at locations $X_1$ and $X_a$ in Fig. 3.9. By applying flexure theory and Hooke's Law, the following equalities are obtained.

$$S_1 = \frac{M_1}{Z} = E \cdot e_1 \quad (3.8)$$

and

$$S_a = \frac{M_a}{Z} = E \cdot e_a \quad (3.9)$$

where: $S_1$ is the maximum compressive normal stress at location $X_1$

$M_1$ is the bending moment at $X_1$

$Z$ is the jaw section modulus

$E$ is the modulus of elasticity for the jaw material

$e_1$ is the maximum compressive strain at $X_1$.

If Eq. 3.7 is written to define the moment at locations $X_1$ and $X_a$, two equations in two unknowns are obtained since the moments are known from Eq. 3.8 and Eq. 3.9.

$$M_1 = F \cdot X_1 - F \cdot X_{c} \quad (3.10)$$

and

$$M_a = F \cdot X_a - F \cdot X_{c} \quad (3.11)$$

If Eq. 3.8 and Eq. 3.9 are multiplied through by the section modulus
Z, the moment can then be substituted for in Eq. 3.10 and Eq. 3.11.

\[ Z \times E \times e_a = F \times X_a - F \times X_w \]  \hspace{1cm} (3.12)

and

\[ Z \times E \times e_1 = F \times X_1 - F \times X_w \]  \hspace{1cm} (3.13)

After simultaneously solving Eq. 3.12 and Eq. 3.13 for the gripping force F, the following relationship is obtained.

\[ F = (e_1 - e_a) \times Z \times E / (X_a - X_1) \]  \hspace{1cm} (3.14)

where: \( X_a > X_1 \)

\( e_1 \) and \( e_a \) are the absolute values of the respective compressive strains.

Teoh, Workman, and Stiles [15] were able to obtain 1.3-ounces of force resolution using an 8-bit analog to digital converter with the 4-gage bridge described earlier. Therefore, the use of an available 12-bit analog to digital converter connected to two bridges through a multiplexer should provide better resolution while employing the method under consideration. A schematic of one of the bridges employing an unloaded gage for temperature and humidity compensation is shown in Fig. 3.10. The compensating gages should be mounted on an unloaded sample of jaw material. According to Holman [16], the gage
Figure 3.10. Strain Gage Bridge for Temperature Compensation.
arrangement shown in Fig. 3.10 compensates for environmental effects by cancelling them. According to Holman [16], the strain at gage $R_1$ causing a resistance change in $R_1$ is

\[ e = \frac{(R_4/R_1) \times \left[ \left( \frac{V_o}{E} + \frac{R_a}{R_a + R_g} \right) \right]}{(1 - \frac{V_o}{E} - \frac{R_a}{R_a + R_g}) - 1} / F \]

(3.15)

where: $R_i$ is the bridge arm resistance ($i=1...4$)
$V_o$ is detected bridge voltage imbalance
$E$ is the constant supply voltage
$F$ is the gage factor.

If Eq. 3.15 can be particularized for each bridge network to produce separate equations for computing $e_i$ and $e_a$ rather than store two calibration curves in the computer memory, then the controlling algorithm could be written in machine language to compute, check for, and respond to grip which exceeds a set point. But, the method was abandoned in favor of a simpler method; described below.

A method of sensing grip by monitoring the motor torque was considered. With the motor cradled in a resilient mounting, the angular deflection could be measured with a resistance pot and Wheatstone bridge. The bridge output could then be converted and monitored by the laboratory mainframe computer. Dillmann [17] used the method for grip control on a scissors-type parallel jaw gripper with a maximum grip of 6-1/2-pounds. But vibration appeared to be
high when the gripper was first operated. Therefore, the possibility existed that the signal to noise ratio would be great enough to require expensive filtering which would prohibit the method from a cost perspective.

However, the torque of a permanent magnet, direct current motor is directly proportional to the current draw under steady state conditions. Therefore, a sampling resistor placed in series with the motor could provide an indication of output torque and ultimately the gripping force. The 24-Volt DC motor pulls 3-amperes when the gripper is stalled and 1/2-ampere when the gripper is in no-load operation. As a torque sensor, a 1/2-ohm, 5-Watt resistor placed in series with the armature would handle the stall load and drop the supply voltage by not more than 1-1/2-Volts. An 0.47-ohm resistor was obtained, and works quite well with the 12-bit analog to digital converter (ADC). Start up transients, which produce current spikes equal in magnitude to those occurring during grasping, are ignored by the computer which controls grip with by a software delay. Therefore, this force sensing method proved to be an economic and simplistic solution to a problem of major consideration.

A wiring elementary diagram is shown in Fig. 3.11 and a computer communications flow diagram is shown in Fig. 3.12 for control of the gripper motor. All hardware designated by CHAN6 is controlled by the channel 6 output relay of the Unimate I/O module board. The external DPDT relay operated by the channel 6 relay is wired to change the
Figure 3.11. Wiring Elementary for the Parallel Jaw Gripper (De-energized State).
Figure 3.12. Intel Computer/Unimate Controller Flow Diagram for Grip and Tightening Torque Control.
direction of gripper jaw motion (gripper opens when channel 6 is logically low). The channel 7 output relay switches the 24-Volt supply through the external CHAN7 relay (gripper closes when channel 7 is logically high and while input channel 4 is not receiving a logically high signal). The Intel mainframe computer takes input from the 0.47-ohm sampling resistor via channel 0-0A and outputs a high signal through a parallel port interface (PPI) to the Unimate input channel 4 relay when a set point for the gripping force has been exceeded. The controlling software is written in FORTRAN and it monitors the ADC continuously.
CHAPTER IV
DESIGN OF THE PERIPHERALS FOR ROBOTIC ASSEMBLY

To understand the resulting peripheral designs, a review of the assembly procedure used is necessary (The reader may want to refer back to the disassembled valve shown in Fig. 2.3.). The assembly procedure is as follows:

1. A Phillips head screw is taken from the upright feeder (shown in the lower photograph of Fig. 4.1 and then identified in Tab. 4.1.) and placed in the tightening fixture.

2. A valve head gasket is taken from an adjacent upright feeder shown in the bottom photograph of Fig. 4.1 and placed upon the tightening fixture.

3. A valve stem is taken from a rotary mechanical feeder shown in Fig. 4.1 (lower photograph) and placed upon the valve head gasket which is upon the tightening fixture.

4. A valve bonnet is taken from the inclined chute feeder shown in the upper photograph of Fig. 4.1 and slid down upon the valve stem which is resting on the tightening fixture.

5. A packing nut which contains packing is taken from the inclined chute feeder shown in the upper photograph of Fig. 4.1 and slid down the valve stem against the valve body.
Figure 4.1. Feeding Equipment.
<table>
<thead>
<tr>
<th>Label Number</th>
<th>Feeder Identification</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Screw Feeder</td>
</tr>
<tr>
<td>2</td>
<td>Valve Gasket Feeder</td>
</tr>
<tr>
<td>3</td>
<td>Valve Bonnet Feeder</td>
</tr>
<tr>
<td>4</td>
<td>Packing Nut Feeder</td>
</tr>
<tr>
<td>5</td>
<td>Valve Handle Feeder</td>
</tr>
<tr>
<td>6</td>
<td>Valve Stem Feeder</td>
</tr>
<tr>
<td>7</td>
<td>Valve Body Feeder with V-Guiding System Shown</td>
</tr>
</tbody>
</table>

Table 4.1. Identification for Feeders Shown in Fig. 4.1.
6. The robot then releases grip to rotate about joint 5, such that the jaws are horizontal. The robot then grasps the packing nut and feeds it downward while the subassembly is tightened at all points.

7. The tightened subassembly is then lifted, inverted and then located temporarily upon a pin (see the pin mounted atop the tightening fixture in the center of the lower photograph of Fig. 4.2).

8. The robot takes a screw from the upright feeder as described in step 1 and places the screw into the tightening fixture.

9. A valve handle is acquired from the inclined chute feeder shown in the upper photograph of Fig. 4.1 and placed upon the tightening fixture.

10. The robot regrasps the subassembly which was temporarily positioned in step 7 and places the splined end of the stem into the valve handle.

11. The robot then exchanges jaw sleeves at the interchanging station shown in Fig. 2.2.

12. The robot then positions itself to wait for the train to bring a valve body near so that it may then follow and pick up a valve body.

13. The robot then places the grasped valve body atop the inverted subassembly, and the tightening fixture tightens and closes the valve while the robot feeds the body downward.
Figure 4.2. Tightening Fixture.
14. The finished valve assembly is then placed in a box for shipping.

To begin with the discussion of the design of the work station peripherals, the parts which are fed by gravity will be considered first.

The packing adjustment nut, valve bonnet, and valve handle are fed down inclined transfers to escapements which terminate those transfers. The original conception included a pneumatically controlled indexing mechanism which would allow passage of only one unit at a time to the escapement. This mechanism was considered necessary to relieve the weight of fed parts acting to prevent the removal of a single part from the escapement. But by experimenting with different angles of inclination, it was discovered that parts could be easily removed from their transfer escapements if the transfers were properly inclined without the aid of an indexing mechanism. While on the subject of gravity feeding, the Phillips head screws and valve head gaskets were fed by tube type feeders mounted in an upright fashion.

The screw feeder has a rubber disc glued to its exit which has a through hole punched just under the screw head diameter. The undersize diameter hole acts to retain the screws in the magazine while dispensing the screws to the robotic gripper one at a time, similar to a paper drinking cup dispenser. The gasket feeder requires
the magazine contents to be forced downward so that the rubber gaskets do not rotate in the tube bore and jam the feeder. The feeder dispenses a gasket down against a pedestal stop so that as the gripper slides a gasket from the feeder, another gasket slips down onto the pedestal. The remaining two parts were not amenable to the gravity feed method discussed previously.

Designing a feeder for the valve stem proved to be difficult because of the way the part was shaped and designed. If the part is gravity fed by rolling the part down an inclined chute, the non-uniform distribution of mass tends to cause part disorientation transfer before it reaches the escapement. The reader can best understand the non-uniform distribution of the part mass by referring back to Fig. 2.3. Another approach was considered where the stem is gravity fed through an upright tube to an escapement, but the sealing end of the stem is machined with a recess for retaining a sealing gasket. That recess tends to stop removal of the stem from the escapement because the handle end of the stem is stopped by the recess during stem removal.

A decision was made to grip the valve stem such that the stem centerline and tool Z-axis are coincident. Two methods of feeding were considered. The method adopted is implemented by the device shown in the lower photograph of Fig. 4.1 and Fig. 4.3 and is described in the next paragraph. The adopted method was chosen for having the beneficial feature of generating a parts buffer upon a
Figure 4.3. Valve Stem Feeder.
rotating table to counteract the loss of parts supply to the feeding device. The buffer is the number of stems on the table between the point of pickup and the magazine which are 180-degrees apart. So the assembly process can continue uninterrupted when the magazine is emptied as long as the time provided by the buffer is utilized to correct the malfunction. The unaccepted method utilizes a horizontal slide operated by a double-acting pneumatic cylinder in lieu of the rotating table, but it lacks the buffer feature just noted because the slide type escapement presents the stems one at a time.

The rotating feeder was developed by trial and error. The feeding operation depends upon the use of ratchet, detent and gate mechanisms. The gate mechanism is mounted on the upright magazine and is operated by a single acting cylinder. A gate mechanism feeds a stem to a cupped recess in the rotary table when the recess is aligned with the tube-type magazine. After a stem has been fed to the table, a detent mechanism, which maintains the angular position of the rotary table, disengages. The detent mechanism is simply an air-retracted, single-acting pneumatic cylinder. After the cylinder piston rod releases the table, a pawl is driven by a single acting cylinder which indexes a ratchet gear one tooth. Since the gear has 12-teeth and the table has 12-recesses, the table rotates 30-degrees and an empty recess is positioned beneath the magazine. At the same time, a stem is placed in a position known to the robot controller for pickup. The detent mechanism re-engages the rotary table and a stem feeding cycle is complete. A different means for feeding the valve body was
employed, but the basis for the method used was similar to the reasoning which led to the choice of method for stem feeding.

A factor influencing the choice of feeding method for the valve body was the desire of the departmental staff to incorporate a conveyor for parts feeding. Since the shape of the valve body is difficult to feed by gravity methods, the use of a conveyor belt for this purpose was a convenient solution. With the high cost of motor driven, closed looped conveyors making them unaffordable, simulation was accomplished with a large scale model train layout which is shown in the lower photograph of Fig. 4.1. The simulation reasonably assumes that the valve bodies are dumped upon a continuously moving conveyor belt with their bonnet openings placed down against the conveyor belt.

The feeding procedure for the valve body orients the part from a semi-random condition. If the bodies are to be taken from the flat cars, they must be aligned with an axis known to the robot so that the robot can track, grasp and remove a body. The alignment is brought about when a body passes through a V-guiding system and it is tunneled to the flat car centerline. When the body has exited from the V-guide, a pair of sheet metal alignment rails complete valve body orientation. The valve body inlet/outlet centerline is aligned with the flat car longitudinal centerline.

The flat car then transports the oriented valve body past an
emitter-detector pair, which is located immediately after the alignment rails. The change of state generated by the pair when the valve body passes is sensed through input channel 2 of the peripheral interface of the robot controller. The train then stops. The controller software will wait for that state change before initiating the next robotic motion. The robot then executes maneuvers which are grasping and then lifting the body from the train. The robot grasps the body when grabbing it at the inlet and outlet openings. After the body is lifted, a relay restarts train motion. The robot then positions the valve body atop the inverted subassembly which is awaiting fastening in the tightening station.

The tightening station is used to tighten fasteners and threaded connections in the assembling of valves. The tightening station utilizes a cordless drill fitted with a Phillips head screwdriver as pictured in Fig. 4.2. The drill is not rigidly mounted in the structure, but it is torsionally damped to absorb the reaction torque when the drill motor stalls during tightening. The drill is controlled with the same FORTRAN program which controls the parallel jaw gripper. The controlling algorithm is the same as that for the gripper except the Intel ADC receives signal through channel 1-1A and the Intel responds to the robot controller input channel 3 through port A of the PPI. A wiring elementary is shown in Fig. 4.4. The plate upon which an assembled valve rests, as shown in Fig. 4.2, is supported by compression, coil springs. This suspension system accomplishes two objectives. First, the feature provides compliance
Figure 4.4. Control Circuit for Tightening Station (De-energized State).
during assembly which is valuable when consideration is given to the fact that the component parts are manufactured to tolerance specifications. Second, the feature provides for compensation when the external splines on the valve stem and the internal splines in the valve handle fail to align when the stem is being inserted into the valve handle.

When the splines of the stem and handle fail to align, the plate upon which the handle is resting is depressed against the coil springs and the microswitch (wired normally closed) opens. The microswitch is wired to input channel 1 of the peripheral interface of the robot controller and the channel state goes logically low for the open microswitch condition. The robot gripper is then rotated through an angular deflection about the tool Z-axis. The leading ends of the internal splines in the handle are tapered such that the splines of the two parts eventually engage as the stem is rotated since the suspension system is compressed.

In closing this section, the resulting peripheral designs which have been previously discussed were the result of attempting to create an affordable and simple simulation of an industrial work station. Simplicity in design was maintained during synthesis so that available scrap and shop time could be effectively utilized. Since the laboratory setting cannot duplicate an industrial production environment in every sense, the longevity of these peripherals in a production setting cannot be predicted. However, the author hopes
that the simulation accomplished by these peripherals will attract outside research funding.
CHAPTER V
PERFORMANCE AND RECOMMENDATIONS

The performance of the flexible assembly system was measured by two variables. Of greatest importance is the amount of time required to assemble a single unit of the product. Secondary to the rate of production is the number and kind of faults which occur during product assembly. A fault occurs when the assembly process is interrupted because of a system malfunction.

The system assembles valves at a rate of one every 7.0-minutes. The robot controller speed setting is 25-percent of default (100.00 on a scale of 0.01 to 327.67). If the speed setting could be increased, the assembly time per valve could be significantly reduced. But an average of 1-fault occurs per product unit and there is currently no fault detection and correction system. At higher speed settings, the author has observed that the sum of human reaction and controller response times to a process fault is an insufficient margin against damage to the robot or its peripherals. Therefore, the speed is kept low to allow laboratory personnel time to react to a perceived fault.

Most of the faults which have occurred are divided into two categories which are cause oriented. The first source of faults is from the level of quality control used in the manufacture of component parts. In these cases, portions of machined surfaces on parts are defective to the point that part to part engagement during fastening
or insertion operations becomes critical. If the valve manufacturer could raise the level of quality control during the manufacture of component parts, faults caused by defective parts could be eliminated.

The other source of faults is rooted in the equipment of the assembly system. The robot controller currently is aware when a valve body is present, when the gripper is open or grasping an object, and when fasteners have been tightened by a tightening fixture. When feeders other than the valve body feeder run empty or when the robot jams parts together which are misaligned, there is no monitoring system or additional sensing to detect and correct these and other assembly equipment related faults. If a fault detection and correction system were developed, assembly system related faults could be automatically dealt with which would negate the need for human intervention.

In closing, the author recommends that the current work station setup be altered to reduce valve assembly time lost to inherent wasted motions and delays as follows:

1. The valve body feeder should be mounted beneath the work station table and an access hole for part acquisition should be cut in the table. The mounting table will better accommodate other peripherals with the model train layout below the table.

2. The tightening station should be mounted below the work
station table close to the robot base with the spring supported plate flush with the table. The remaining feeders can be mounted closely around the tightening station to reduce lost manipulator motion.

3. A pair of jaw sleeves should be designed to accomplish all grasping tasks of assembly to eliminate the delay associated with automatic jaw sleeve exchange.
REFERENCES


APPENDIX A

GEAR TRAIN DESIGN COMPUTATIONS

AND GRIPPER TEST
An alternate gear train composed of Delrin spur gears was considered in an effort to reduce the surface area occupied by the gear train and to increase the lead screw torque which is available at stall. The minimization of the gear train surface area was desired to eliminate the possibility of gripper interference when approaching the work station peripherals. However, the increase in gear ratio increases multiplication of torque at the expense of reducing the maximum jaw speed when the gripper is closing or opening. The kinematic representation of that gear train is shown in Fig. A.1. The cataloged data for the gear train considered is

\[
\begin{align*}
N_1 &= 28 & D_1 &= 0.5833\text{-in.} \\
N_2 &= 80 & D_2 &= 1.6667\text{-in.} \\
N_3 &= 36 & D_3 &= 0.7500\text{-in.} \\
N_4 &= 100 & D_4 &= 2.0833\text{-in.} \\
\end{align*}
\]

3/16-in. face width

where \(N_i\) is the number of gear teeth \((i=1\ldots4)\)

\(D_i\) is the gear diameter (inch).

The gear ratio is calculated from

\[
\frac{n_4}{n_1} = \left(\frac{N_2}{N_1}\right) \times \left(\frac{N_4}{N_3}\right) = \frac{80}{28} \times \frac{100}{36} = 7.94
\]

(A.1)
Figure A.1. Alternate Gripper Gear Train.
where \( n_i \) is the angular velocity of the gear (i=1...4).

The required gear center to center distances for zero backlash are

\[
C_1 = \frac{(D_1 + D_2)}{2} \tag{A.2}
\]

\[
= \frac{(0.5833 + 1.6667)}{2}
\]

\[
C_1 = 1.125\text{-in.}
\]

where \( C_1 \) is the gear center to center distance for the mesh of gear 1 and 2.

and

\[
C_4 = \frac{(D_4 + D_4)}{2} \tag{A.3}
\]

\[
= \frac{(0.7500 + 2.0833)}{2}
\]

\[
C_4 = 1.417\text{-in.}
\]

The center to center distance for gear 1 and 4 is 2.542-inches.
The lead screw torque at stall for this arrangement is 143. inch-ounces (motor stall torque of 18. inch-ounces) which provides a margin over the 120. inch-ounces required to produce a 15-pound grip.

The gear tooth stress levels are checked by the method described in Chapter I under motor stall conditions. Since for gear 1 the tooth bending stress and safety factor are unchanged from that computed,
Eq. 3.3 is first applied to gear 2.

\[ S = W_e \times \frac{P}{F/Y} \]
\[ = (2 \times T_m \times \frac{P}{28}) \times \frac{P}{F/Y} \]
\[ = 2797 \times 0.353/0.437 \]
\[ S = 2260-lb./sq. \text{ in.} \]

The safety factor is 4.43. For gear 3,

\[ S = (2 \times (143./16) \times 48/100) \times 48/(3/16)/0.378 \]
\[ S = 5810-lb./sq. \text{ in.} \]

The safety factor is 1.72 for gear 3. Finally for gear 4,

\[ S = 5811 \times 0.378/0.447 \]
\[ S = 4910-lb./sq. \text{ in.} \]

The safety factor is 2.04 for gear 4. The last two safety factors are not marginal when it is understood that load sharing among meshed teeth is not accounted for in the development of Eq. 2.3.
Figure A.2. Coil Spring Calibration Curve for Testing Parallel Jaw Gripper.
APPENDIX B

DRAWINGS SUPPLIED TO SHOP
Figure B.1. Gripper Base Plate Drawing.
Figure B.2. Gripper Motor Mounting Components.
Figure B.3. Provision for Adapter Mounting of Pneumatic Gripper.
Figure B.4. Detent for Retaining Jaw Sleeves.
APPENDIX C

PRINTOUT OF SOFTWARE

FOR

CONTROL OF ASSEMBLY
C PROGRAM TORQCCTRL

J=0
CALL OUTPUT(#86H,#80H)
CALL OUTPUT(#4011H,#19H)
1 DO 2 I=1,1000
2 CALL OUTPUT(#80H,#FFH)
100 CALL OUTPUT(#4010H,#01H)
CALL CHECK(L)
IF(L.LE.535)GO TO 200
J=J+1
IF(J.LE.200)GO TO 100
IF(J.LE.600)GO TO 100
DO 10 M=1,1000
10 CALL OUTPUT(#80H,#F7H)
J=0
200 CALL OUTPUT(#4010H,#00H)
CALL CHECK(L)
IF(L.LE.535)GO TO 1
J=J+1
IF(J.LE.200)GO TO 200
IF(L.LE.575)GO TO 200
DO 20 N=1,2000
20 CALL OUTPUT(#80H,#EFH)
J=0
GO TO 1
END

SUBROUTINE CHECK(L)
INTEGER*1 I,J
DO 10 K=1,100
10 CONTINUE
CALL INPUT(#4012H,J)
CALL INPUT(#4013H,I)
IF(J.GE.0)GO TO 20
L=256*(I+1)+J
GO TO 30
20 L=I*256+J
30 RETURN
END
PROGRAM ASSEMBLEVLV
1. SETI B = 1
2. SETI A = 1
3. IF SIG 5, , , , THEN 100
4. GOSUB OPENGIRPR
5. 100 GOSUB GETSCREW
6. GOSUB PLACESCREW
7. GOSUB GETGASKET
8. GOSUB PLACEGASKET
9. GOSUB RELEASEFDRTABLE
10. GOSUB GETVLVSTEM
11. GOSUB VLSTMFDRCNTRL
12. GOSUB PLACEVLVSTEM
13. GOSUB GETBONNET
14. GOSUB PLACEBONNET
15. GOSUB GETNUT
16. GOSUB PLACENUT
17. GOSUB JOINASSEM
18. GOSUB PLACETEMPORARY
19. GOSUB GETSCREW
20. GOSUB PLACESCREW
21. GOSUB GETHANDLE
22. GOSUB PLACEHANDLE
23. GOSUB GETSUBASSEM
24. GOSUB PLACESUBASSEM
25. GOSUB FIXHANDLE
26. GOSUB CHANGESLEEVE1
27. GOSUB GETBODY
28. GOSUB PLACEBODY
29. GOSUB FIXBODY
30. GOSUB BOXVLV
31. GOSUB CHANGESLEEVE2
32. SETI B = B + 1
33. IF B LE 6 THEN 100
34. HALT

PROGRAM OPENGIRPR
1. SIGNAL -6, , , , , ,
2. SIGNAL 7, , , , , ,
3. WAIT 5
4. SIGNAL -7, , , , ,
5. RETURN 0
PROGRAM GETSCREW
1. MOVE SCREW1
2. DRAW 0.00, 0.00, -436.94
3. GOSUB CLOSEGRIPR1
4. DRAW 0.00, 0.00, -15.00
5. DEPARTS 28.56
6. DRAW 0.00, 0.00, 435.91
7. DRIVE 6, 180.00, 200.00
8. RETURN 0

PROGRAM CLOSEGRIPR1
1. SIGNAL 6, , , , , ,
2. SIGNAL 7, , , , , ,
3. DELAY 0.30
4. WAIT 4
5. SIGNAL -7, , , , , ,
6. RETURN 0

PROGRAM PLACESCREW
1. DRIVE 1, -50.999, 200.00
2. MOVE SCREW2
3. DRAW 0.00, 0.00, -339.19
4. GOSUB RELEASEGRIP
5. DRAW 0.00, 0.00, 339.19
6. GOSUB OPENGRIPR
7. RETURN 0

PROGRAM RELEASEGRIP
1. SIGNAL -6, , , , , ,
2. SIGNAL 7, , , , , ,
3. DELAY 0.40
4. SIGNAL -7, , , , , ,
5. RETURN 0
PROGRAM GETGASKET
1. DRIVE 1, 68.011, 200.00
2. DRIVE 6, -180.00, 200.00
3. MOVE GASKET1
4. DRAW 0.00, 0.00, -346.47
5. GOSUB CLOSEGRIPR1
6. DEPARTS 30.00
7. DRAW 0.00, 0.00, 346.47
8. DRIVE 6, 180.00, 200.00
9. RETURN 0

PROGRAM PLACEGASKET
1. DRIVE 1, -60.002, 200.00
2. MOVE GASKET2
3. DRAW 0.00, 0.00, -311.44
4. GOSUB STARTDRILL
5. DELAY 7.00
6. SPEED 3.00
7. DRAW 0.00, 0.00, -7.00
8. GOSUB STOPDRILL
9. DRAW 0.00, 0.00, 3.00
10. GOSUB RELEASEGRIP
11. DRAW 0.00, 0.00, 318.44
12. GOSUB OPENGRIPR
13. RETURN 0

PROGRAM STARTDRILL
1. SIGNAL 8, , , , , , , , ,
2. RETURN 0

PROGRAM STOPDRILL
1. SIGNAL -8, , , , , , , , ,
2. RETURN 0

PROGRAM RELEASEFDRTABLE
1. SIGNAL 3, , , , , , , , ,
2. RETURN 0
PROGRAM GETVLVSTEM
1. DRIVE 1, 83.002, 200.00
2. MOVE VLVSTM1
3. GOSUB ADJUSTJAWS
4. DRAW 0.00, 0.00, -440.69
5. DRAW -6.03, 6.47, 0.00
6. GOSUB CLOSEGRIPR1
7. DEPARTS 462.78
8. RETURN 0

PROGRAM ADJUSTJAWS
1. SIGNAL 6, , , , , ,
2. SIGNAL 7, , , , , ,
3. DELAY 1.20
4. SIGNAL -7, , , , , ,
5. RETURN 0
PROGRAM VLVSTMFDRCNTRL
1. 10 IF A GT 1 THEN 20
2. GOSUB POSHOLE1
3. GOTO 200
4. 20 IF A GT 2 THEN 30
5. GOSUB POSHOLE2
6. GOTO 200
7. 30 IF A GT 3 THEN 40
8. GOSUB POSHOLE3
9. GOTO 200
10. 40 IF A GT 4 THEN 50
11. GOSUB POSHOLE4
12. GOTO 200
13. 50 IF A GT 5 THEN 60
14. GOSUB POSHOLE5
15. GOTO 200
16. 60 IF A GT 6 THEN 70
17. GOSUB POSHOLE6
18. GOTO 200
19. 70 IF A GT 7 THEN 80
20. GOSUB POSHOLE7
21. GOTO 200
22. 80 IF A GT 8 THEN 90
23. GOSUB POSHOLE8
24. GOTO 200
25. 90 IF A GT 9 THEN 100
26. GOSUB POSHOLE9
27. GOTO 200
28. 100 IF A GT 10 THEN 110
29. GOSUB POSHOLE10
30. GOTO 200
31. 110 IF A GT 11 THEN 120
32. GOSUB POSHOLE11
33. GOTO 200
34. 120 GOSUB POSHOLE12
35. SETI A = 1
36. GOTO 210
37. 200 SETI A = A + 1
38. 210 RETURN 0
PROGRAM POSHOLE1
1. SIGNAL 2, , , , ,,
2. DELAY 0.90
3. SIGNAL 4, , , , ,,
4. DELAY 0.24
5. SIGNAL -3, , , , ,,
6. DELAY 0.90
7. SIGNAL -2, , , , ,
8. SIGNAL -4, , , , ,
9. RETURN 0

PROGRAM POSHOLE2
1. SIGNAL 2, , , , ,
2. DELAY 0.90
3. SIGNAL 4, , , , ,
4. DELAY 0.24
5. SIGNAL -3, , , , ,
6. DELAY 0.90
7. SIGNAL -2, , , , ,
8. SIGNAL -4, , , , ,
9. RETURN 0

PROGRAM POSHOLE3
1. SIGNAL 2, , , , ,
2. DELAY 0.90
3. SIGNAL 4, , , , ,
4. DELAY 0.24
5. SIGNAL -3, , , , ,
6. DELAY 0.90
7. SIGNAL -2, , , , ,
8. SIGNAL -4, , , , ,
9. RETURN 0

PROGRAM POSHOLE4
1. SIGNAL 2, , , , ,
2. DELAY 0.90
3. SIGNAL 4, , , , ,
4. DELAY 0.24
5. SIGNAL -3, , , , ,
6. DELAY 0.90
7. SIGNAL -2, , , , ,
8. SIGNAL -4, , , , ,
9. RETURN 0
PROGRAM POSHOLE5
1. SIGNAL 2, , , , , ,
2. DELAY 0.90
3. SIGNAL 4, , , , , ,
4. DELAY 0.21
5. SIGNAL -3, , , , , ,
6. DELAY 0.90
7. SIGNAL -2, , , , , ,
8. SIGNAL -4, , , , , ,
9. RETURN 0

PROGRAM POSHOLE6
1. SIGNAL 2, , , , , ,
2. DELAY 0.90
3. SIGNAL 4, , , , , ,
4. DELAY 0.23
5. SIGNAL -3, , , , , ,
6. DELAY 0.90
7. SIGNAL -2, , , , , ,
8. SIGNAL -4, , , , , ,
9. RETURN 0

PROGRAM POSHOLE7
1. SIGNAL 2, , , , , ,
2. DELAY 0.90
3. SIGNAL 4, , , , , ,
4. DELAY 0.23
5. SIGNAL -3, , , , , ,
6. DELAY 0.90
7. SIGNAL -2, , , , , ,
8. SIGNAL -4, , , , , ,
9. RETURN 0

PROGRAM POSHOLE8
1. SIGNAL 2, , , , , ,
2. DELAY 0.90
3. SIGNAL 4, , , , , ,
4. DELAY 0.26
5. SIGNAL -3, , , , , ,
6. DELAY 0.90
7. SIGNAL -2, , , , , ,
8. SIGNAL -4, , , , , ,
9. RETURN 0
PROGRAM POSHOLE9
1. SIGNAL 2, , , , , ,
2. DELAY 0.90
3. SIGNAL 4, , , , , ,
4. DELAY 0.25
5. SIGNAL -3, , , , , ,
6. DELAY 0.90
7. SIGNAL -2, , , , , ,
8. SIGNAL -4, , , , , ,
9. RETURN 0

PROGRAM POSHOLE10
1. SIGNAL 2, , , , , ,
2. DELAY 0.90
3. SIGNAL 4, , , , , ,
4. DELAY 0.27
5. SIGNAL -3, , , , , ,
6. DELAY 0.90
7. SIGNAL -2, , , , , ,
8. SIGNAL -4, , , , , ,
9. RETURN 0

PROGRAM POSHOLE11
1. SIGNAL 2, , , , , ,
2. DELAY 0.90
3. SIGNAL 4, , , , , ,
4. DELAY 0.26
5. SIGNAL -3, , , , , ,
6. DELAY 0.90
7. SIGNAL -2, , , , , ,
8. SIGNAL -4, , , , , ,
9. RETURN 0

PROGRAM POSHOLE12
1. SIGNAL 2, , , , , ,
2. DELAY 0.90
3. SIGNAL 4, , , , , ,
4. DELAY 0.26
5. SIGNAL -3, , , , , ,
6. DELAY 0.90
7. SIGNAL -2, , , , , ,
8. SIGNAL -4, , , , , ,
9. RETURN 0
PROGRAM PLACEVLVSTEM
1. DRIVE 1, -89.000, 200.00
2. MOVE VLVSTM2
3. DRAW 0.00, 0.00, -240.47
4. SPEED 9.00
5. DRAW 0.00, 0.00, -10.00
6. SPEED 9.00
7. DRAW 0.00, 0.00, 1.50
8. GOSUB RELEASEGRIP
9. DEPARTS 250.00
10. GOSUB OPENGRIPR
11. RETURN 0

PROGRAM GETBONNET
1. DRIVE 1, 61.002, 200.00
2. MOVE BONNET1
3. DRAW 0.00, 0.00, -310.41
4. GOSUB CLOSEGRIPR1
5. SPEED 200.00
6. DEPARTS 25.00
7. DRAW 0.00, 0.00, 241.81
8. RETURN 0

PROGRAM PLACEBONNET
1. DRIVE 1, -60.002, 200.00
2. MOVE BONNET2
3. DRAW 0.00, 0.00, -190.00
4. SPEED 9.00
5. DRAW 0.00, 0.00, -40.00
6. GOSUB RELEASEGRIP
7. DEPARTS 230.00
8. GOSUB OPENGRIPR
9. RETURN 0

PROGRAM GETNUT
1. MOVE NUT1
2. DRAW 0.00, 0.00, -352.44
3. GOSUB CLOSEGRIPR1
4. DEPARTS 20.00
5. DRAW 0.00, 0.00, 240.00
6. RETURN 0
PROGRAM PLACENUT
1. MOVE NUT2
2. DRAW 0.00, 0.00, -216.00
3. SPEED 9.00
4. DRAW 0.00, 0.00, -18.00
5. GOSUB RELEASEGRIP
6. DEPARTS 234.00
7. GOSUB OPENGRIPR
8. RETURN 0

PROGRAM JOINASSEM
1. GOSUB GRASPNUT
2. GOSUB JOINPARTS
3. RETURN 0

PROGRAM GRASPNUT
1. MOVE NUT3
2. DRAW 0.00, 0.00, -400.00
3. GOSUB CLOSEGRIPR1
4. RETURN 0

PROGRAM JOINPARTS
1. GOSUB STARTDRILL
2. SPEED 1.60
3. DRAW 0.00, 0.00, -9.53
4. DELAY 2.00
5. SPEED 3.60
6. DRAW 0.00, 0.00, -13.00
7. DELAY 2.00
8. SPEED 2.00
9. DRAW 0.00, 0.00, -3.81
10. WAIT 3
11. GOSUB STOPDRILL
12. SPEED 9.00
13. DRAW 0.00, 0.00, 12.00
14. RETURN 0
PROGRAM PLACETEMPORARY
1. DRAW 0.00, 0.00, 50.00
2. DRAW -53.53, -81.59, 0.00
3. DRIVE 6, -180.00, 200.00
4. DRAW 0.00, 0.00, -78.00
5. SPEED 9.00
6. DRAW 0.00, 0.00, -20.00
7. GOSUB OPENGRIPR
8. DRAW 0.00, 0.00, 340.00
9. DRIVE 1, 64.001, 200.00
10. RETURN 0

PROGRAM GETHANDLE
1. MOVE HANDLE1
2. DRAW 0.00, 0.00, -121.59
3. GOSUB CLOSEGRIPR1
4. DEPARTS 40.00
5. DRAW 0.00, 0.00, 100.00
6. RETURN 0

PROGRAM PLACEHANDLE
1. MOVE HANDLE2
2. DRAW 0.00, 0.00, -340.00
3. SPEED 9.00
4. DRAW 0.00, 0.00, -10.00
5. GOSUB OPENGRIPR
6. GOSUB STARTDRILL
7. DELAY 5.00
8. GOSUB STOPDRILL
9. DEPARTS 100.00
10. RETURN 0
PROGRAM GETSUBASSEM
1. DRAW -56.06, -81.41, 0.00
2. DRAW 0.00, 0.00, -100.91
3. GOSUB CLOSEGRIPR1
4. DEPARTS 87.00
5. RETURN 0

PROGRAM PLACESUBASSEM
1. MOVE SUBASSEM1
2. SPEED 3.00
3. DRAW 0.00, 0.00, -40.00
4. DRIVE 6, -22.50, 3.00
5. RETURN 0

PROGRAM FIXHANDLE
1. GOSUB STARTDRILL
2. SPEED 1.60
3. DRAW 0.00, 0.00, -8.00
4. WAIT 3
5. GOSUB STOPDRILL
6. SPEED 9.00
7. DEPARTS 12.00
8. GOSUB OPENGRIIPR
9. DEPARTS 260.00
10. RETURN 0

PROGRAM CHANGESLEEVES1
1. DRIVE 1, -79.003, 200.00
2. DRIVE 6, -164.00, 200.00
3. MOVE GRIPPER1
4. DRAW 0.00, 0.00, -284.94
5. SPEED 0.01
6. DRAW 0.00, 34.66, 0.00
7. SPEED 0.01
8. DEPARTS 10.00
9. DEPARTS 70.00
10. DRAW 0.00, 0.00, 60.00
11. DRIVE 6, 180.00, 200.00
12. MOVE GRIPPER2
13. DRAW 0.00, 0.00, -60.00
14. SPEED 0.01
15. DEPARTS -10.00
16. DEPARTS -44.38
17. SPEED 0.01
18. DEPARTS -25.00
19. SPEED 0.01
20. DRAW 0.00, 34.66, 0.00
21. DRAW 0.00, 0.00, 284.94
22. RETURN 0
PROGRAM GETBODY
1. DRIVE 1, 82.002, 200.00
2. MOVE BODY
3. GOSUB WHEREISVLVBODY
4. DRAW 0.00, 0.00, -372.44
5. GOSUB CLOSEGRIPR1
6. DRAW 0.00, 0.00, 372.44
7. RETURN 0

PROGRAM WHEREISVLVBODY
1. WAIT -2
2. RETURN 0

PROGRAM PLACEBODY
1. MOVE BODY1
2. DRAW 0.00, 0.00, -100.00
3. RETURN 0

PROGRAM FIXBODY
1. SPEED 2.00
2. DRAW 0.00, 0.00, -9.00
3. DRIVE 6, -90.00, 100.00
4. DRIVE 6, 180.00, 100.00
5. GOSUB STARTDRILL
6. SPEED 2.00
7. DRAW 0.00, 0.00, -9.00
8. SPEED 2.00
9. DRAW 0.00, 0.00, -3.00
10. DELAY 2.00
11. SPEED 3.60
12. DRAW 0.00, 0.00, -7.00
13. WAIT 3
14. GOSUB STOPDRILL
15. DRAW 0.00, 0.00, 26.00
16. RETURN 0
PROGRAM BOXVLV
1. IF B GT 1 THEN 10
2. SETI R = 1
3. SETI C = 1
4. SET SPOT = CORNER
5. 10 GOSUB LOADVLV
6. SHIFT SPOT BY 0.00, 120.00, 0.00
7. SETI R = R + 1
8. IF R LE 3 THEN 20
9. SHIFT SPOT BY 130.00, 0.00, 0.00
10. SHIFT SPOT BY 0.00, -360.00, 0.00
11. SETI R = 1
12. SETI C = C + 1
13. IF C LE 2 THEN 20
14. SHIFT SPOT BY -260.00, 0.00, 0.00
15. SETI C = 1
16. SET SPOT = CORNER
17. 20 RETURN 0

PROGRAM LOADVLV
1. MOVE ABOVE
2. MOVE SPOT
3. GOSUB OPENGRIPR
4. MOVE ABOVE
5. RETURN 0

PROGRAM CHANGESLEEVES2
1. MOVE GRIPPER3
2. DRAW 0.00, 0.00, -284.94
3. SPEED 0.01
4. DRAW 0.00, -34.66, 0.00
5. SPEED 0.01
6. DEPARTS 10.00
7. DEPARTS 69.38
8. DRAW 0.00, 0.00, 60.00
9. DRIVE 6, -180.00, 200.00
10. MOVE GRIPPER4
11. DRAW 0.00, 0.00, -60.00
12. SPEED 0.01
13. DEPARTS -10.00
14. DEPARTS -45.00
15. SPEED 0.01
16. DEPARTS -25.00
17. SPEED 0.01
18. DRAW 0.00, -34.66, 0.00
19. DRAW 0.00, 0.00, 315.00
20. DRIVE 1, 130.00, 200.00
21. RETURN 0
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<tr>
<th>Component</th>
<th>X/JT1</th>
<th>Y/JT2</th>
<th>Z/JT3</th>
<th>O/JT4</th>
<th>A/JT5</th>
<th>T/JT6</th>
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<td>ABOVE</td>
<td>435.59</td>
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<td>36.47</td>
<td>45.901</td>
<td>88.901</td>
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<td>142.16</td>
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<td>9.59</td>
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<td>89.039</td>
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<td>BONNET1</td>
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<td>-5.125</td>
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<td>CORNER</td>
<td>288.41</td>
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<td>-409.41</td>
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<td>GASKET1</td>
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<td>-163.34</td>
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<td>X/JT1</td>
<td>Y/JT2</td>
<td>Z/JT3</td>
<td>O/JT4</td>
<td>A/JT5</td>
<td>T/JT6</td>
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<td>-------</td>
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<tr>
<td>SCREW1</td>
<td>256.38</td>
<td>424.72</td>
<td>37.06</td>
<td>132.182</td>
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<td>SUBASSEM1</td>
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<td>50.202</td>
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<td>115.00</td>
<td>-5.125</td>
<td>89.467</td>
<td>0.000</td>
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APPENDIX D
SPECIFICATIONS
FOR
SYSTEM OPERATION
<table>
<thead>
<tr>
<th>Item</th>
<th>Set Point</th>
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<tbody>
<tr>
<td>Monitor Speed Setting of Unimate Controller</td>
<td>25.00</td>
</tr>
<tr>
<td>Air Supply Pressure</td>
<td>55 to 60-lb./sq.in.</td>
</tr>
<tr>
<td>Battery Supply</td>
<td>2.55-Volt DC</td>
</tr>
<tr>
<td>Valve Stem Feeder</td>
<td>Align hole #12 under vertical feeding tube.</td>
</tr>
<tr>
<td>Robot Configuration</td>
<td></td>
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<tr>
<td>Prior to Calibration</td>
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</table>

Model Railway Transformer Settings

<table>
<thead>
<tr>
<th>Speed</th>
<th>Direction</th>
<th>Pulse</th>
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<tr>
<td>18-percent of full scale.</td>
<td>Counterclockwise.</td>
<td>On.</td>
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Table D.1. Specifications for Operation.