

The Grasping and Manipulation of Irregularly Shaped Objects with Application to Semiconductor Industry

by

Anthony Christopher Leier

Bachelor of Science in Mechanical Engineering
Massachusetts Institute of Technology (1996)

Submitted to the
Department of Mechanical Engineering
in partial fulfillment of the requirements for the degree of

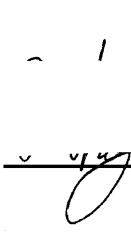
Master of Science in Engineering

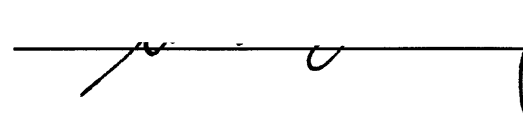
at the


Massachusetts Institute of Technology

June, 1998

© 1998 Massachusetts Institute of Technology

Signature of Author  _____
Department of Mechanical Engineering
May 8, 1998

Certified By  _____
Steven Dubowsky
Thesis Supervisor

Accepted By  _____
Ain A. Sonin
Chairman, Departmental Graduate Committee

MASSACHUSETTS INSTITUTE OF TECHNOLOGY

AUG 04 1998

LIBRARIES

Acknowledgments

I would like to thank Professor Steven Dubowsky for the opportunity to work in his laboratory. I'd also like to thank my project colleagues, Joseph Calzaretta, Vivek Sujan, and Melissa Tata for being a great team to work with. Also, thanks to all the other guys in the lab group for their advice and friendship. Thanks to Dr. Longsheng Yu for all of his help with the wrist design. Thanks to David Bevly for his help debugging the wrist electronics. Thanks to Dick Fenner and Tony Cieri of the Pappalardo Lab for all of their help during the past couple of years.

I acknowledge and appreciate the support from the project's sponsor, Shin-Etsu Handotai Co., Inc.

And most of all, thanks to Leah Schechter for all the help, support, understanding, love, and everything else.

Table of Contents

1 Introduction	
1.1 Background and Problem Description.....	8
1.2 Literature and Gripper Review.....	10
1.3 Purpose of this Thesis.....	13
1.4 Outline of this Thesis.....	13
2 Requirements and Design Objectives	
2.1 Introduction.....	16
2.2 Crucible Filling Requirements.....	16
2.2.1 SEH process requirements.....	17
2.2.2 Nugget characterizations.....	19
2.3 RACS Demonstration System Overview.....	22
2.3.1 Description of the RACS.....	22
2.3.2 RACS operation.....	23
2.4 RACS Requirements for the End Effector.....	26
2.5 Summary and Conclusions.....	27
3 Design of the Robotic End Effector	
3.1 Introduction.....	29
3.2 System Overview.....	29
3.3 Stroke Extension.....	31
3.4 Wrist Design.....	33
3.4.1 Wrist specifications.....	34
3.4.2 Wrist control electronics.....	36
3.5 Gripper Design.....	37
3.5.1 Vacuum cup selection.....	38
3.5.2 Gripper specifications.....	46

3.5.3	Pneumatic system design.....	47
3.6	Bulk Filler design.....	49
4	Nugget Grasping Performance	
4.1	Introduction.....	52
4.2	Pressure and Air Flow Requirements.....	52
4.3	Nugget Grasping Test Results.....	57
4.3.1	Grasping force experiment.....	57
4.3.2	Nugget grasping test.....	58
4.4	Bulk Filling Operation.....	61
4.5	Conclusions and Summary.....	66
5	Conclusions	
5.1	Contributions of this Thesis.....	67
5.2	Application to the RACS Factory System.....	68
5.3	Suggestions for Further Work.....	71
References		
Appendix		
A	Adept One Mechanical Specifications.....	78
B	Force Sensor Mechanical Specifications.....	82
C	Wrist Control Circuitry.....	84
D	Test Nugget Characteristics.....	86
E	Vacuum Pump Specifications.....	89

List of Figures

Figure 2.1	Crucible Filled with Silicon Nuggets.....	18
Figure 2.2	Silicon Nuggets, Top View.....	19
Figure 2.3	Silicon Nuggets, Side View.....	20
Figure 2.4	Nugget Size Distribution.....	21
Figure 2.5	RACS Demonstration System.....	22
Figure 2.6	RACS Crucible Filling Procedure.....	24
Figure 3.1	Overall End Effector Design.....	30
Figure 3.2	Photograph of the End Effector Without the Air Cylinder.....	31
Figure 3.3	Stroke Extension Air Cylinder.....	32
Figure 3.4	Air Cylinder Control System.....	33
Figure 3.5	End Effector Wrist Design.....	34
Figure 3.6	Wrist Control Electronics Flow Chart.....	36
Figure 3.7	Vacuum Cup Testing Apparatus.....	40
Figure 3.8	Difficult to Grasp Nuggets, Top and Side Views.....	42
Figure 3.9	Vacuum Cup Lip Profiles.....	43
Figure 3.10	VI-CAS Vacuum Cup Model B3-1.....	44
Figure 3.11	Gripper Design.....	46
Figure 3.12	Gripper Pneumatic System Schematic.....	48
Figure 3.13	Bulk Filling Bin Design.....	49
Figure 3.13	Photograph of the Bulk Fill Bin.....	50
Figure 4.1	Manifold Pressure Experiment Apparatus.....	53
Figure 4.2	Manifold Pressure Variation During the Pressure Experiment.....	56

Figure 4.3	Pressure Test Results	56
Figure 4.4	Bulk Filling Regions within an 18" Crucible.....	61
Figure 4.5	Bulk Filling Operation.....	62
Figure 4.6	Bulk Fill Pouring with the End Effector.....	64
Figure 4.7	Bulk Filling Pour Pattern.....	65
Figure 5.1	Overhead View of the Factory RACS.....	69
Figure 5.2	Side View of the Factory RACS.....	70
Figure A.1	Adept One Dimensions.....	79
Figure A.2	Adept One Workspace.....	80
Figure A.3	Adept One Base Mounting Dimensions.....	80
Figure A.4	Adept One User Flange Dimensions.....	81
Figure B.1	JR ³ Sensor, Outline Drawing.....	83
Figure C.1	Wrist Control Circuit Diagram.....	85
Figure D.1	Nugget Cross Sectional Area vs. Mass.....	88
Figure E.1	Vacuum Pump Specifications.....	89

Chapter 1

Introduction

1.1 Background and Problem Description

An automated factory system, the Robot Assisted Crucible Charging System (RACS), has been developed for Shin-Etsu Handotai Co. (SEH) of Japan. SEH is the world's largest producer of silicon wafers used in the semiconductor manufacturing industry (SEH America web site, 1998). SEH produces pure, monocrystalline silicon through the Czochralski (CZ) crystal growth process (Wolf and Tauber, 1986), in which a perfect silicon seed crystal is slowly rotated and pulled from pure (except for a precise amount of added dopants) molten silicon contained in a fused silica (99% SiO₂) crucible. A typical crucible is a cylinder 18 inches in diameter, 14 inches high, with a gently curved bottom and open top. The crucible holds approximately 70 kg of silicon. From the silicon crystal seed grows a cylindrical, monocrystalline ingot of silicon. This crystal is cut into wafers, polished, and sent to integrated circuit manufacturers (Wolf and Tauber, 1986).

SEH is currently expanding their silicon wafer manufacturing facilities in order to make 300 mm (12 inch) diameter monocrystalline silicon ingots.

To successfully grow crystals of this size, approximately 530 kg of silicon is needed. To accommodate this silicon charge, the size of the crucibles in which the silicon nuggets are melted must be increased, in this case to 36 inches in diameter. SEH currently manually fills crucibles with electronics grade polycrystalline silicon nuggets of irregular shape and size (hereafter referred to as nuggets). SEH determined that manually filling the new 36 inch crucibles would be difficult due to worker fatigue and reach limitations. Robotic systems are often used to overcome these human limitations (Meyer, 1985), so the RACS has been developed to fill the new crucibles. The RACS design project has two goals: a laboratory demonstration of the needed technologies, and the development of a factory system concept based upon these technologies.

The development of the RACS has been divided into four parts. This thesis deals with the design and development of the mechanical systems of the RACS. In particular, it addresses the end effector for the robot. Preliminary work on the gripper design was completed in *Gripper Design for the Robot Assisted Crucible Charging System* (Garcia, 1997). The control system for the manipulation of the nuggets is described in detail in "*Delicate Manipulation of Irregularly-shaped Rigid Objects in a Stiff, Fragile Environment*" (Calzaretta, 1998). The vision system and nugget packing algorithms used to determine the placement locations for the nuggets within the crucible are described in "*Sensor Based Manipulation of Irregularly Shaped Objects with Special Application to Semiconductor Industry*" (Sujan,

1998). The concepts for the factory system application of this technology are currently being developed.

1.2 Literature and Gripper Review

The challenging task for the development of the RACS end effector is the grasping of irregular silicon nuggets, and the literature review focuses on this topic. Generally, end effectors, and grippers especially, are custom designed for particular applications (Fan Yu, 1982; Potter, 1985). Each robotic application is different in process, operating environment, and workpieces. As a rule, the features of the part to be grasped determine the gripper design (Micallef, 1986).

A review of gripper literature found four basic gripper design types: clamping grippers, vacuum and magnetic grippers, universal grippers, and specialty grippers (Lundstrom *et al.*, 1977; Fan Yu, 1982; Wright and Cutkosky, 1985; Kato and Sadamoto, 1987; Rehg, 1997). Clamping grippers are the most common design and are usable for most robotic applications. Clamping gripper types include: parallel jaw, angular closing jaw, clamping fingers, interior clamping, and interior expanding. Clamping grippers require at least two opposing surfaces in order to grasp an object. Vacuum and magnetic grippers can pick up parts using one object face. Magnetic grippers can only lift ferric materials, while vacuum grippers are generally used for items with flat and smooth surfaces, and in limited cases for irregular objects (Mannaa *et al.*, 1991). Universal grippers are designed to grasp a variety of parts without

reconfiguration of the gripper. Mechanical hands are the most common type of universal gripper (Tanie, 1985; Holzbock, 1986). Universal gripper designs that grasp a part by enveloping it are given by (Perovskii, 1986; Scott, 1986). Specialty grippers are often application specific, and many times the actual grasping of an object is a secondary task for the robot. These grippers include customized tooling such as fastener drivers, painting and welding end effectors, and grippers developed for a single, specific work piece.

Examination of gripper designs showed that vacuum or universal grippers would be most appropriate for the RACS. Clamping grippers are normally only used in applications where work piece shapes and locations are known, for these grippers are generally not tolerant to object irregularities, and therefore not appropriate for a RACS. Clamping grippers in conjunction with vision systems have been used to grasp objects with irregular positions and regular shapes (Bach *et al.*, 1985; Neal *et al.*, 1997).

Mechanical hands, the most common type of universal gripper, were first examined for use in grasping silicon nuggets. Development of mechanical hands is a major research topic in gripper research (Cutkosky, 1985; Mason, 1985; Salisbury, 1985). In particular, planning how to grasp objects with mechanical hands is a common research area (Stansfield, 1991; Gorce and Fontaine, 1996; Shimoga, 1996). Work has been done in grasping unknown, possibly irregular objects using a vision system and mechanical hand gripper (Bianchi and Rovetta, 1986; Stansfield, 1991; Trobina and Leonardis, 1995). Universal grippers usage outside of research projects in

industry is currently not widespread, for the technology is still being developed (Rehg, 1997).

After reviewing mechanical hands and universal grippers, it became apparent that these would not work within the RACS. All of the universal grippers must grasp objects using opposed surfaces, generally the sides of the object. In the RACS, an arbitrary point on the side of the grasped nugget must be able to come into contact with the side of the crucible in which the nugget is placed. The fingers of a mechanical hand would interfere with this requirement. Vacuum grippers, which require only a single contact surface, became the choice for gripper type.

Vacuum grippers are for the most part used to lift objects with smooth, dry, clean, and airtight surfaces (Kato and Sadamoto, 1987). Vacuum grippers are also used in the handling of fabrics (Kolluru *et al.*, 1995), the manipulation of flat, non-rigid materials (Karakerezis *et al.*, 1994), and the lifting of micro-objects (Zesch *et al.*, 1997). Since vacuum cups are made out of compliant materials such as rubber and plastic, vacuum grippers have a natural tolerance of part orientation errors and are better able to conform to irregular shapes and rough workpieces (Wright and Cutkosky, 1985). A vacuum gripper and vision system have been used to successfully grasp irregularly oriented, regularly shaped parts in a bin (Tella *et al.*, 1982; Tella and Birk, 1986). The ability to adapt to irregular surfaces and grasp objects on only one surface promoted the use of a vacuum gripper in the RACS.

1.3 Purpose of this Thesis

This thesis addresses the problem of grasping and manipulating irregularly shaped objects for a specific industrial application. Robotic manipulation of irregularly *shaped* objects was rarely discussed in reviewed literature, though various systems that grasp irregularly *oriented* objects were found. This document describes the research completed in developing a gripper that can grasp irregularly shaped objects (polysilicon nuggets) as part of an end effector system.

The end effector designed for the RACS is presented along with the functional requirements that led to the design. The experiment to determine the gripper's vacuum cup shape, size, and configuration is described, and the results of the experiment are discussed.

The gripper manifold pressure must be regulated to ensure adequate vacuum pressure and air flow through the vacuum cups. The desired gripper pressure characteristics are described, and a method to tune the gripper pressures is given. The downward force needed to grasp nuggets robotically is presented. The test performed to determine the grasping ability of the gripper is described, and the results of the test are given. The usage and operational characteristics of the bulk filling bin are illustrated.

1.4 Outline of this thesis

This thesis is divided into five chapters. Chapter 1 introduces the project and provides a context for the work. Chapter 2 gives the parameters

provided by SEH for the project, characterizes the polysilicon nuggets that are to be manipulated, and describes the newly developed RACS laboratory demonstration.

Chapter 3 presents the design of the RACS end effector and related systems. A custom vacuum gripper has been built to grasp silicon nuggets. In the system, the nugget must be oriented through six degrees of freedom, making necessary an addition of a wrist to a four degree of freedom Adept One robot. A bulk filling device, which the robot uses to place the small and ungraspable nuggets into the crucible, is then presented.

Chapter 4 describes the experiments that have been completed to optimize and demonstrate the effectiveness of the end effector. The determination of the vacuum pressure and flows necessary for nugget grasping is presented first. After the vacuum pressure and flows have been set, the grasping ability of the gripper is measured and characterized. Finally the bulk filling of the nuggets is reviewed.

Chapter 5 concludes with an overview of the operation of the end effector systems within the whole RACS. Suggestions on applying this end effector technology to a RACS factory system are given.

The appendices give specifications for parts of the RACS and additional information on polysilicon nuggets that were used in experiments. Appendix A provides the mechanical specifications of the Adept One robot used in the demonstration system. Appendix B presents the mechanical specifications of the JR³ force/torque sensor used in the system. Appendix C

gives the schematic for the circuitry developed to control the end effector's wrist. Appendix D lists the properties of the set of nuggets that were used in system tests. Appendix E gives the specifications of the system's vacuum pump.

Chapter 2

Requirements and Design Objectives

2.1 Introduction

This chapter describes the parameters under which the RACS and its end effector were designed. Section 2.2 gives the crucible filling requirements specified by SEH. The physical characteristics of the silicon nuggets that are grasped are also presented. Section 2.3 describes the RACS demonstration system and illustrates RACS operation. Section 2.4 discusses the requirements placed upon the end effector design by the RACS system level design.

2.2 Crucible Filling Requirements

The irregular silicon nuggets must be manipulated within a SEH crucible charging factory system. SEH currently manually fills crucibles, and the requirements of that manual process apply to robotically filling the crucibles. Since the purpose of the end effector is to grasp and manipulate nuggets, the physical characteristics and size distribution of silicon nuggets are a key parameter.

2.2.1 SEH process requirements

Silicon filled crucibles are used by SEH in CZ crystal growth. The requirements for a properly filled crucible come from SEH's experience in crucible filling and using the CZ process. The most important requirement is that no contamination may be added to the silicon during crucible filling. Electronics grade silicon is one of the purest materials commonly used in industry, with impurity levels in the parts per billion range (Wolf and Tauber, 1986). Great care must be taken to prevent the introduction of contaminants into the silicon. Additionally, damage to the crucible can add unwanted silica particles to the silicon melt. Some contamination from the crucible during the melt process is inevitable; however, any contamination should be minimized.

The next requirement is that nuggets must be placed within the crucible correctly. To better understand the work environment, the physical properties of the fused silica crucibles are given in Table 2-1, (from Shackelford *et al*, 1994).

Table 2-1: Properties of Fused Silica Crucible

Composition:	99% SiO ₂ , 1% impurities
Silica Density:	2.094 g/cm ³
Melting Point:	1723°C: Softens prior to melt
Hardness:	500-679 Vickers (kg/mm ²)

The RACS must place nuggets within the entire volume of a crucible. Nuggets are also placed above the rim of the crucible as a crown. Within the

crucible volume, the mass of silicon placed should be as high as possible (resulting in larger monocrystalline silicon ingots). A comparison between the 18 inch diameter crucibles used in the laboratory demonstration system and the proposed 36 inch crucibles is in Table 2-2.

Table 2-2 Comparison of 18" and 36" Crucibles

CHARACTERISTIC	18" Crucible	36" Crucible
Crucible Height	14"(35.6 cm)	23.5"(59.7 cm)
Stacking wall height	11.4"(29 cm)	18.7"(47.5 cm)
Contained Volume	3,263 in ³ (53,471 cm ³)	21,726 in ³ (356,025 cm ³)
Crown Volume (3" average height)	764 in ³ (12,520 cm ³)	3,054 in ³ (50,046 cm ³)
Total Volume	4,027 in ³ (65,991 cm ³)	24,780 in ³ (406,071 cm ³)
Charge Weight	70 kg	~530 kg
Estimated RACS charging time	53 min	225 min
Manual charging time	30 min	360 min (estimated)

Nuggets must be loaded into a crucible under certain parameters to ensure proper melt characteristics, illustrated in Figure 2-1 (Dubowsky, 1997).

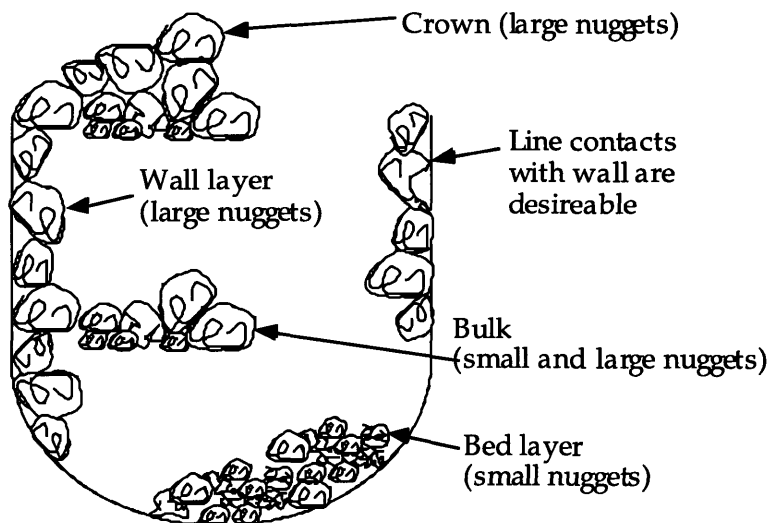


Figure 2-1: Crucible Filled with Silicon Nuggets

Flat nugget surfaces contacting the crucible wall can result in nuggets sticking to the crucible wall during melting, and a misbuilt crown can cause a nugget bridge that will remain at the top of the crucible while its support melts. Both of these conditions can result in nuggets falling and causing an undesirable splash in the molten silicon. Nuggets contacting the crucible wall with a sharp point is not desirable, since a stress concentration is introduced at the point, making crucible damage more likely. The preferred wall contact is with multiple points or a line.

2.2.2 Nugget characterizations

The properties of the nuggets to be grasped should be known in order to determine and evaluate a grasping method. The silicon nuggets are irregular in both size and shape, as demonstrated in Figure 2-2 and Figure 2-3 with top and side views of the same nuggets.

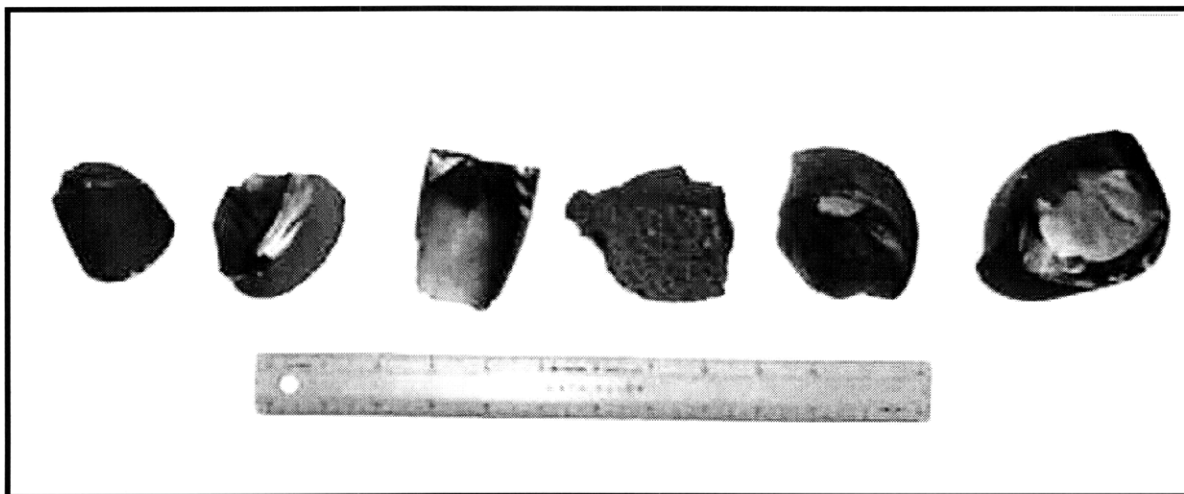


Figure 2-2: Silicon Nuggets, Top View

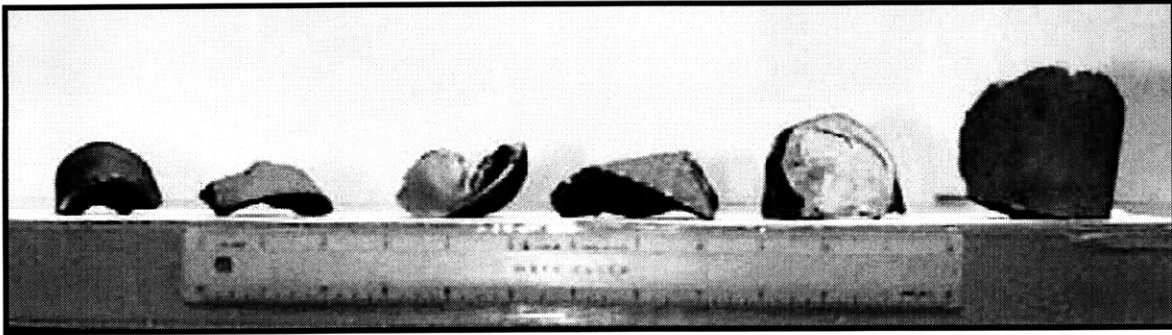


Figure 2-3: Silicon Nuggets, Side View

As the pictures show, the nuggets that are used do not have regular features, shapes, or sizes. However, nuggets can be qualitatively divided according to surface shape and quality. Some nuggets have a characteristic mottled surface texture, while others display especially jagged angles. Also, the process by which the nuggets are made tends to produce cylinders and fragments of cylinders. Polycrystalline silicon nuggets are hard, brittle, and do not show regular cleavage. Physical properties of silicon are given in Table 2-3, (from Dietz *et al.*, 1981).

Table 2-3: Properties of Silicon

Crystal Structure:	Diamond lattice
Density at 20°C:	2.33 g/cm ³
Density at melting point:	2.55 g/cm ³
Melting point:	1420° C
Boiling point:	2630° C
Hardness:	1000 Vickers (kg/mm ²)

A 70 kg nugget sample with approximately 1000 nuggets above 10 grams in weight was weighed and classified by size (Garcia, 1997). A histogram of the results is shown in Figure 2-4.

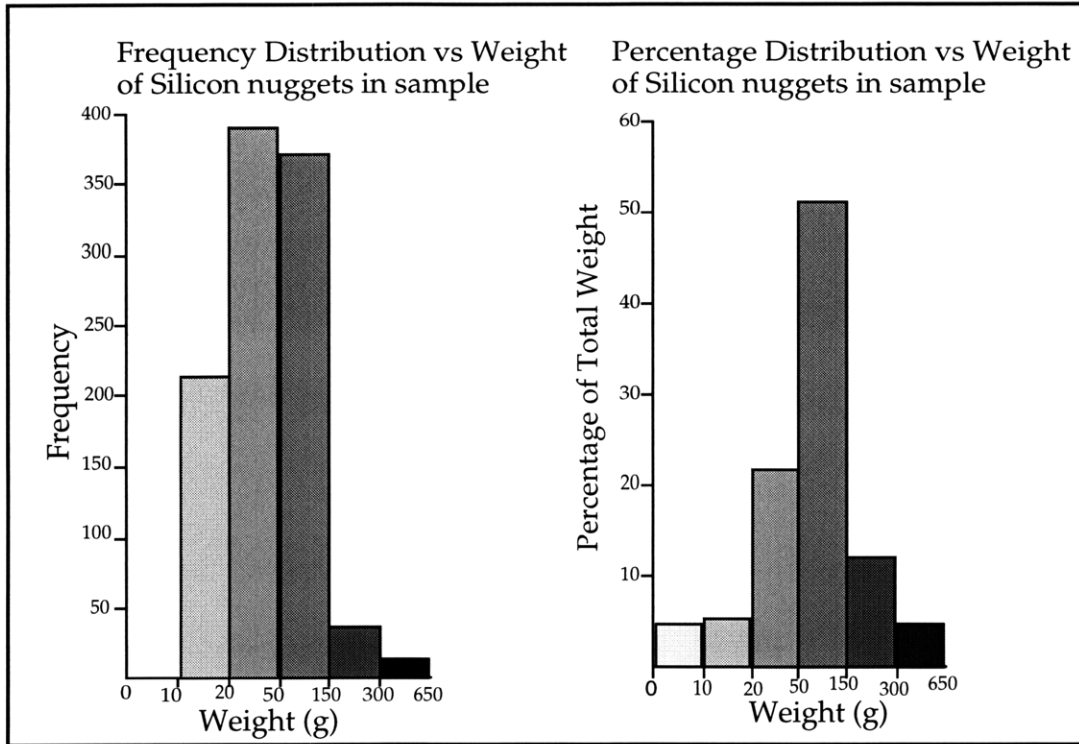


Figure 2-4: Nugget Size Distribution

The frequency of nuggets below 10 grams was not recorded, since these nuggets were many small fragments, pebbles, and silicon dust. The majority of the nuggets fall between 20 and 150 grams in weight, with those nuggets from 50 to 150 grams making up the bulk of the weight. In the RACS, nuggets above 80 grams in weight (approximately 350 nuggets in a 70 kg sample size, averaging 130 g) are classified as “large” and those below 80 grams are “small”. The large nuggets can be individually placed against the crucible wall, in the crown, or as central bulk fill, while the small nuggets form the bed and bulk fill (see also Figure 2-1).

2.3 RACS Demonstration System Overview

The end effector design presented in this thesis is part of an automation system. A physical description of the RACS and a basic understanding of how the system operates is needed to give a context for the end effector design. Further information on the RACS development project can be found in (Dubowsky, 1997). The system level design and operation of the laboratory demonstration RACS are described, and the requirements that the system places on the end effector are listed. Refer to (Calzaretta, 1998) for details on the control system and to (Sujan, 1998) for details on the vision system and nugget packing algorithm.

2.3.1 Description of the RACS

The RACS laboratory demonstration system, shown in Figure 2-5, fills a fused-silica crucible with silicon nuggets.

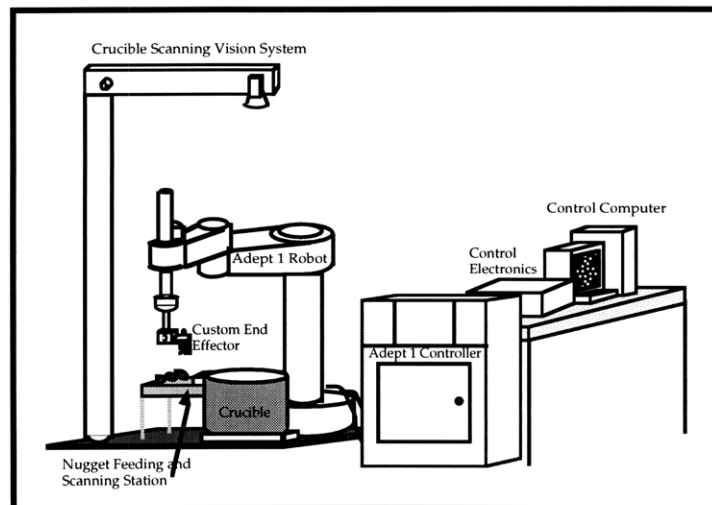


Figure 2-5: RACS Demonstration System

An Adept One SCARA Robot (Adept Technology Inc, 1997) with a customized controller (Goldenberg *et al.*, 1989) is the main component of the demonstration RACS. The Adept One controller has been modified to accept torque control commands from the control computer. All of the RACS operations are controlled through the control computer and associated electronics. Attached to the end flange of the robot are a JR³ six axis force/torque sensor (JR³ Inc., 1988) and the end effector described by this thesis. Within the robot workspace rest the crucible to be filled, a nugget feeding area where nuggets and bulk fill bins can be picked up, and the nugget scanning vision system. The crucible scanning vision system scans from overhead, outside of the robot's workspace.

2.3.2 RACS operation

During RACS operation, a human operator sorts nuggets by size and places the larger nuggets on a conveyor leading to the robot so that the grasping difficulty of each nugget is minimized (experience has shown that, with a little practice, orienting the nuggets while placing them requires little extra time or effort). The operator receives the nuggets in 5 kg bags of random shapes and sizes of nuggets. The smaller nuggets and unwanted large nuggets are placed directly into a bulk fill bin or placed on a separate transfer line that fills the bulk filling bins. The operator also inspects the quality of the nuggets, checking for contaminants and other problems. The large nuggets and small nuggets are used in different filling processes. Figure 2-6 gives an overview of the crucible filling process. Details on each filling process follow the figure.

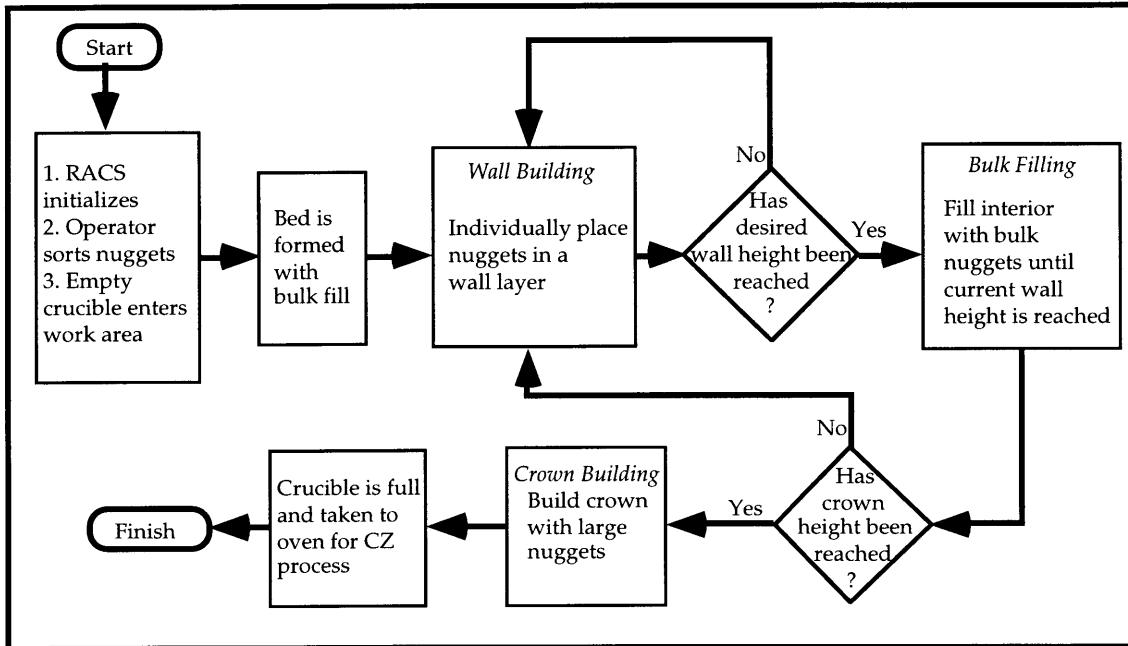


Figure 2-6: RACS Crucible Filling Procedure

Wall and crown building

A RACS goes through the following procedure to place a large nugget in a wall layer or in the crown of a crucible:

1. A large nugget from the conveyor is grasped by the robot with a vacuum gripper. The nugget's location need only be known location to within ± 5 mm.
2. The robot moves the nugget over the nugget scanning vision system, which determines the bottom surface geometry of the grasped nugget.
3. While the nugget is being grasped and scanned, the overhead crucible scanning vision system maps the nuggets already within the crucible.

4. The data from the nugget scan are compared to the data from the crucible scan, and an appropriate placement location for the nugget within the crucible is found by the computer.
5. The robot moves the nugget to above the placement location within the crucible.
6. The nugget is gently brought against the side wall of the crucible and carefully lowered into its position. Wall contact force is kept below a level that would cause scratching.
7. The nugget is released by the vacuum gripper in the designated placement location
8. The robot returns to the nugget feeding station to pick up the next nugget, and the process repeats until the desired wall or crown height is reached.

Bulk filling

Small and unused large nuggets are poured into the crucible as bedding or center fill with the bulk filling bins through the following procedure:

1. The robot picks up a filled bin from the bulk fill loading site.
2. The packing algorithm determines the location within the crucible where the bulk fill should be poured.
3. The robot moves the bulk fill bin to just above the designated fill location within the crucible.
4. The bulk fill is poured into the crucible.

5. The empty bulk fill bin is removed from the crucible and returned to the bulk filling feeding station.
6. The bin is released and the next filled bin is picked up. The procedure repeats until the desired bulk fill level is reached.

The packing algorithm determines what crucible filling regime is appropriate for the current crucible fill level. When the required amount of silicon in the crucible or the desired crown height is reached, the crucible is full and taken to the ovens for the next stage in CZ crystal growth. An empty crucible is put within the RACS and the filling process begins again.

2.4 RACS Requirements for the End Effector

The end effector must work within the designed laboratory system. In order for the RACS demonstration system to be successful, the end effector must be able to:

- Successfully grasp and manipulate at least 85% of the large (80 grams and above) silicon nuggets in order to completely fill an 18" diameter crucible.
- Grasp and manipulate the bulk filling bin.
- Bring a nugget against the crucible's wall throughout the crucible.
- Orient nuggets through ± 180 degrees of yaw and ± 15 degrees of both pitch and roll so that any nugget surface within this envelope can come into direct contact with the wall.

- Place and release a nugget without significantly disturbing nuggets already in the crucible.
- Accommodate a force/torque sensor as required by the control scheme.

A successful grasp is one in which the nugget is held through all necessary manipulations, maintains consistent orientation within the grasp, and satisfies the placement requirements mentioned above. The end effector needs to be robust and reliable. The cost and required maintenance should also be minimized.

System interfaces

The end effector is controlled by the system computer, and should easily interface with the computer. The wrist motors and pneumatic valves are operated through the control computer. Wrist position information is needed by the control scheme, necessitating wrist position sensors. A method to detect nugget pickup is also required by the system.

2.5 Summary and Conclusions

The mechanical system must meet all of the presented requirements. The end effector must be able to successfully grasp irregular nuggets, move the nuggets to the appropriate crucible locations, and place the nuggets in the desired locations. The purity of the silicon may not be affected, and the crucible must not be damaged. The end effector must operate within the

laboratory demonstration system and be appropriate for use in a factory RACS. Additionally, the system should be appropriate for the lab environment in which it was built and tested. The components should be minimal in cost, easy to construct, easy to control and use, and robust.

Chapter 3

Design of the Robotic End Effector

3.1 Introduction

This chapter discusses the design of the end effector for the laboratory demonstration RACS. The design and specifications of the components are given. Section 3.2 gives an overview of the end effector system. Section 3.3 describes the air cylinder stroke extension. Section 3.4 depicts the three degree of freedom wrist and associated electronics. Section 3.5 describes the gripper design and the justification for the design. The bulk filling design is discussed in Section 3.6.

3.2 System Overview

The purpose of the end effector is to orient and place a nugget in a specified place within a crucible. To achieve this goal, the system shown in Figure 3-1 was designed. The end effector is mounted to a JR³ Universal Force-Moment Sensor System that is attached to the end flange of an Adept One SCARA robot. Specifications for the Adept One can be found in Appendix A, and specifications for the JR³ sensor are in Appendix B.

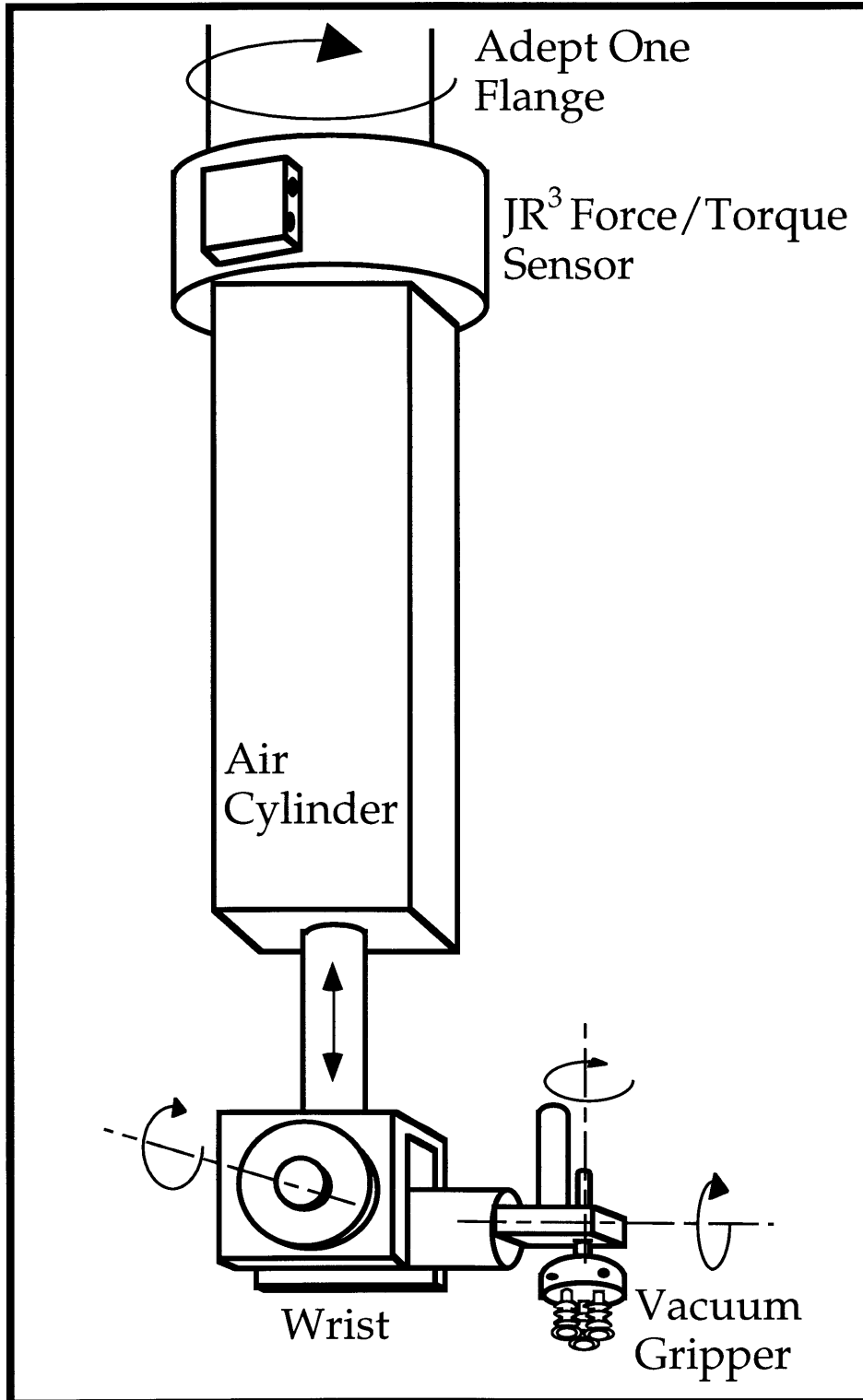


Figure 3-1: Overall End Effector Design

An air cylinder with a stroke of 150 mm (6 in.) is connected to the sensor. This cylinder extends the stroke of the robot to the 350 mm (13.75 in.) needed

to reach the bottom of an 18 inch diameter crucible. A three degree of freedom wrist is mounted to the air cylinder. The vacuum gripper is attached to the end of the wrist. The control electronics for the wrist and the vacuum pneumatic system for the gripper are not shown. Figure 3-2 is a picture of the constructed the laboratory system end effector, without the air cylinder, which has yet to be implemented in the system.

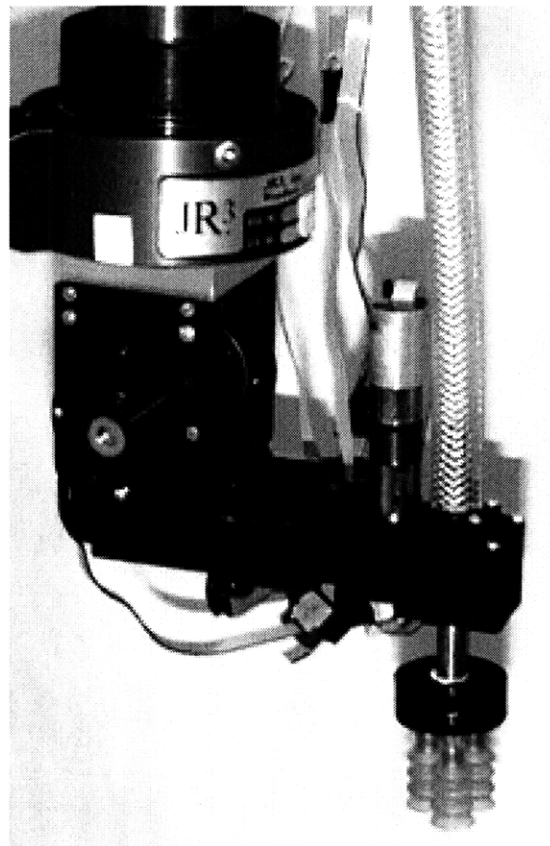


Figure 3-2: Photograph of the End Effector without the Air Cylinder

3.3 Stroke Extension

To completely fill a crucible, vertical robot motion of 350 mm is required. The Adept One robot used in the laboratory demonstration system has only a 200mm (7.7 in) vertical stroke, so a stroke extension is necessary.

A single-axis linear translation of 150mm (6 in) is the most efficient way to extend the stroke of a SCARA configuration robot arm. The stroke extension need only have two positions, retracted and extended, since the Z axis of the Adept One can provide any required incremental motion. The translation device also must support the wrist, gripper, and grasped items under static and dynamic loads.

A pneumatic cylinder was determined to be best suited for fulfilling the requirements of the stroke extension. Air cylinders are easy to control, provide two definite positions (retracted and extended), are available in many configurations, and are commonly used for such applications such as this. A Fabco-Air air cylinder (Fabco-Air, 1996) was found that meets the needs of the system. A schematic diagram of this cylinder is shown in Figure 3-3.

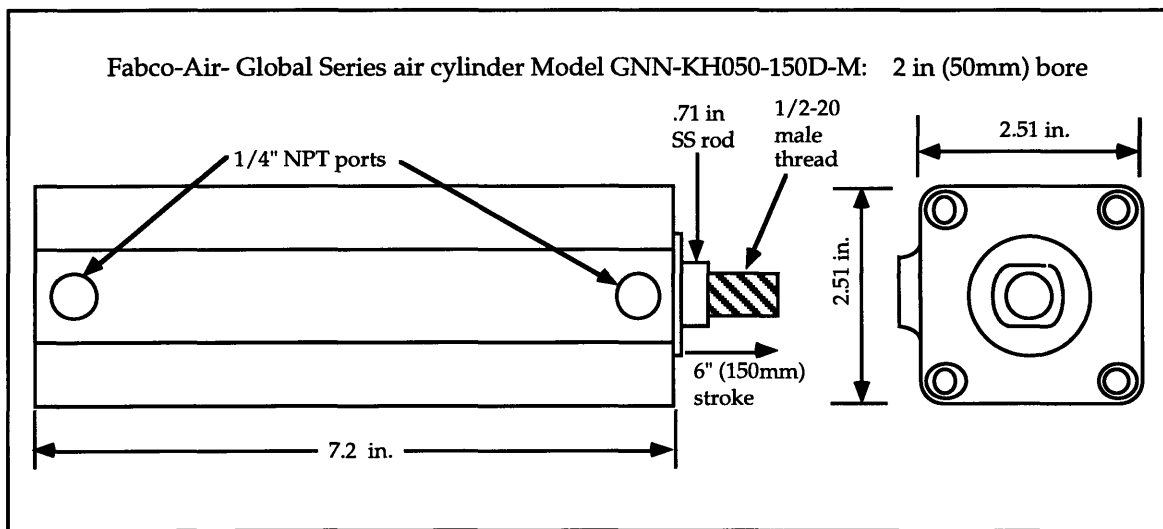


Figure 3-3: Stroke Extension Air Cylinder

The cylinder meets required stroke specifications and can exert 200 N of force at 4 atmospheres of pressure. The cylinder is larger than the nugget lifting requirement would indicate, because the piston also serves as a structural

support for the wrist and gripper. The piston rod's stiffness is great enough to avoid structural resonances caused by robot motion. The air cylinder is controlled with a Fabco-Air four-way solenoid valve. This valve will be operated through the RACS control computer. A schematic of the air cylinder control system is given in Figure 3-4.

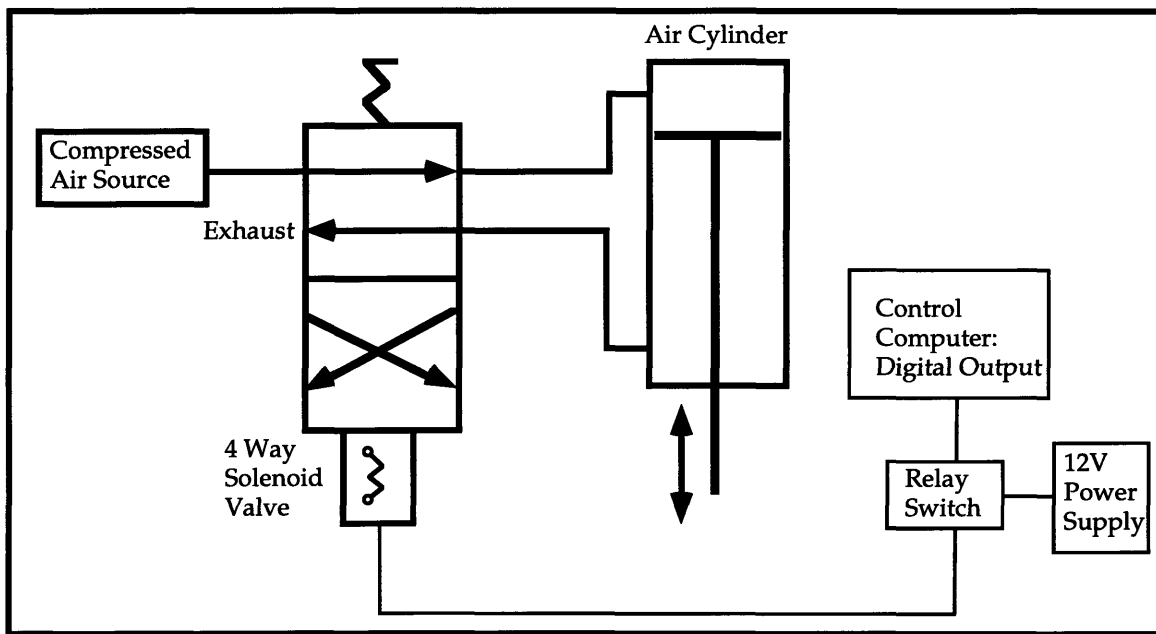


Figure 3-4: Air Cylinder Control System

An air cylinder with a smaller bore could be used instead if it had external support in the form of guide rails or a linear slide. However, this solution proved to take up just as much space as a single, larger cylinder and to be more expensive. The presented design is a simpler way to extend the stroke of the Adept One.

3.4 Wrist Design

The mechanical system for the end effector wrist was designed and constructed by Dr. Longsheng Yu with the author's assistance. The

mechanical design is described here for completeness. Recall that the major requirement for the wrist is that it must move nuggets $\pm 15^\circ$ in both pitch and roll (rotation about the x and y axes) and $\pm 180^\circ$ in yaw (z axis rotation). These motions are required by the nugget packing algorithm of the system (Sujan, 1998). The wrist system should also be as small as possible, interface simply with the air cylinder and gripper, and include the electronics necessary for system operation and control.

3.4.1 Wrist Specifications

The wrist developed for the laboratory demonstration system is depicted in Figure 3-5 (drawn by Dr. Longsheng Yu). The wrist is capable of $+30^\circ/-60^\circ$ of pitch, $\pm 90^\circ$ of roll, and continuous yaw rotation.

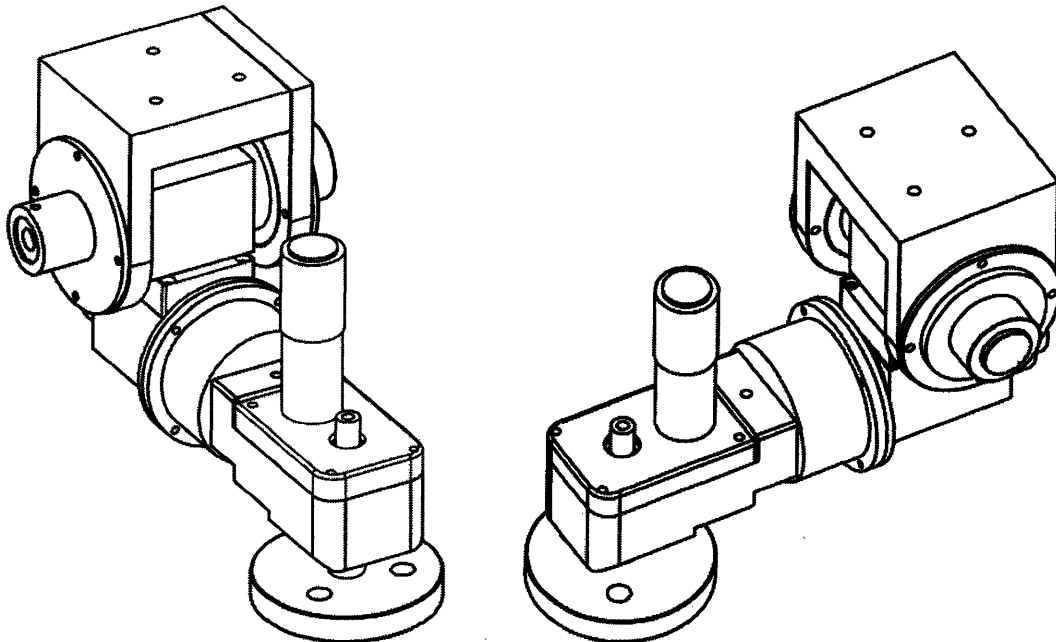


Figure 3-5: End Effector Wrist Design

The first two joints, pitch and roll, are configured in a gimbal. Joint three, yaw, is offset from the main robot axis and represents a seventh degree of freedom for the RACS. This additional degree of freedom is necessary since the geometry of the robot and attached end effector require the gripper to be offset from the axis of the robot. Without the offset, the force sensor, piston, or parts of the wrist would come into contact with the crucible wall before a grasped nugget could.

Three Micro Mo 12 volt DC motors (Micro Mo, 1996) move the joints of the wrist. Specifications of the motors, gearheads, and encoders are given in Table 3-1.

Table 3-1: Wrist Motor Specifications

Motor model No.:	2224U012SR	1624T012S
Position in wrist:	Joints 1 and 2	Joint 3
Armature resistance (Ohms):	8.71	24
Max output power (W):	4.13	1.5
Stall torque (mN-m):	19.9	4.23
Torque constant (mN-m/Amp):	14.6	8.64
Gearhead model:	23/1	16/7
Gear ratio:	245.9615:1	245.9615:1
Maximum gearhead torque, continuous/intermittent (mN-m):	700/1000	300/450
Gear efficiency:	60%	60%
Magnetic encoder model:	IE2-16	HEM-1624T16
Encoder pulses per revolution:	16	16
Total weight (g):	146	68

Two Micro Mo model 2224R motors power the first two joints. The motors are housed within the shafts of the joints, decreasing the volume taken up by the wrist. A Micro Mo model 1624 motor moves the third joint, which rotates the gripper plate about the plate's axis. The joint three motor is offset

from the gripper axis by two spur gears with a 2:1 ratio. This offset allows the vacuum line from the vacuum pump to attach to the gripper manifold through the axis of the gripper plate. A single air line to the gripper plate manifold allows a simple O-ring assembly to be used to decouple the gripper rotation from the non-rotating vacuum line.

3.4.2 Wrist Control Electronics

The three, 12 volt DC motors in the wrist and their associated encoders are controlled through the RACS control computer. A circuit was designed by Joseph Calzaretta and the author to interface the motors and encoders with the computer. The operation of the control electronics is illustrated in Figure 3-6. A complete circuit diagram is given in Appendix C.

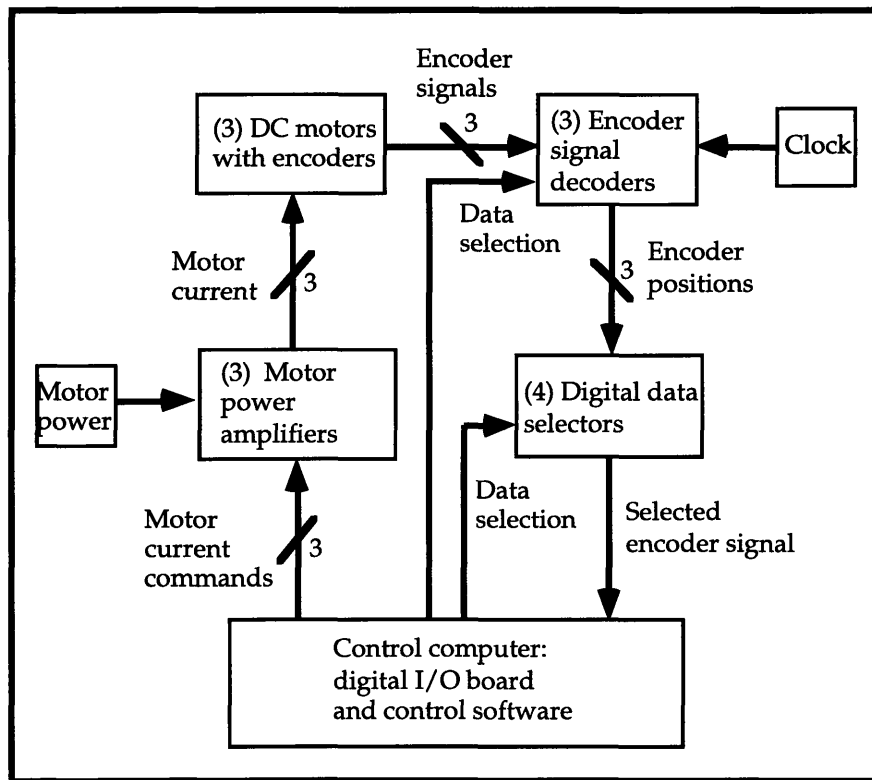


Figure 3-6: Wrist Control Electronics Flow Chart

The circuit converts the quadrature encoder signals into digital signals through three Hewlett-Packard HCTL2016 16 bit 4x quadrature decoders. A set of four 74ALS253 TTL Data Selectors/Multiplexors converts the three encoder positions to a single, selected output signal. Selected encoder positions are then read by the control computer. Torque control of the motors is achieved through three current regulating National Semiconductor LMD18245 DMOS full bridge motor drivers. An Analogic PDIO-72 digital I/O card connects the control circuitry to the control computer.

3.5 Gripper Design

The component of the end effector that presented the largest technical challenge is the gripper. The gripper must grasp a variety of irregular silicon nuggets reliably, securely, and without contamination of the nuggets. To maximize nugget packing density in a crucible, the RACS requires that a nugget be able to make wall contact at an arbitrary location around the nugget's edge. This allows the packing algorithm to find optimal placement locations for nuggets. Furthermore, the gripper should not disturb previously placed nuggets in the crucible when placing a new nugget in the crucible. Therefore, any gripper that must grasp a nugget by clamping opposing surfaces (the sides) would not be appropriate for the task. Vacuum, magnetic, and adhesive grippers can grasp objects by one face. Silicon is not ferric, making magnetic gripping impossible, and adhesives would contaminate the silicon; therefore, a vacuum gripper was chosen. Vacuum

grippers are also well suited to the grasping challenge, since the inherent compliance of vacuum cups makes the gripper tolerant of irregularities in nugget shape and position.

3.5.1 Vacuum cup selection

The first step in developing a vacuum gripper was to determine the vacuum cup material, size, number, and configuration. Vacuum cups are commonly made of rubber, such as silicone and neoprene, or soft plastic, such as vinyl. Vinyl operator's work gloves are currently used by SEH to contact nugget surfaces. Preliminary nugget grasping tests were done using silicone rubber vacuum cups (Garcia, 1997); however, silicone rubber is not appropriate for nugget contact, so vinyl was chosen as the material for vacuum cups.

After cup material is selected, the cup size is chosen. The lifting force of a vacuum cup is determined by the area of the cup. To pick up a .75 kg load (slightly larger than the largest nugget in our sample) with a 90% vacuum source, and assuming a perfect cup seal onto the grasped object, a vacuum cup area of .71 cm² is required. A cup size of twice this area is needed to lift a fully loaded bulk filling bin. The calculated cup area is not sufficient for use in grasping nuggets, since the quality of a vacuum seal to a silicon nugget is low, due to the irregular nature of the nugget surfaces. The required cup area is therefore better determined empirically. The shape of a vacuum cup also greatly influences sealing ability, and the best vacuum cup shape is again found experimentally.

Vacuum cup size and shape determination apparatus

A selection of 20 vinyl vacuum cups (VI-CAS Manufacturing, 1997) of various sizes and shapes was ordered to perform tests to find the optimal vacuum cup for grasping nuggets. A set of twenty nuggets was chosen based upon the nuggets' anticipated grasping difficulty. This set is representative of the most difficult nugget surfaces to grasp; if a gripper can reliably grasp this set, then the gripper could grasp any of the nuggets in the lab's sample. The challenging surfaces can be divided into two categories: sloped or jagged surfaces that do not present flat areas to grasp, and rough surface textures that prevent a cup from making an airtight seal. The difficult surface of each nugget was labeled with a number, so that the nugget surfaces to be grasped remained constant throughout the testing. Details on the characteristics of the twenty nuggets can be found in Appendix D.

To test the grasping ability of the vacuum cup selection, each cup was used singly to grasp each of the 20 nuggets. A cup was mounted to a gripper testing plate and was supplied with a vacuum pressure of .90 atmospheres with minimal flow resistance from the end effector's vacuum pump. The apparatus for the experiment is shown in Figure 3-7.

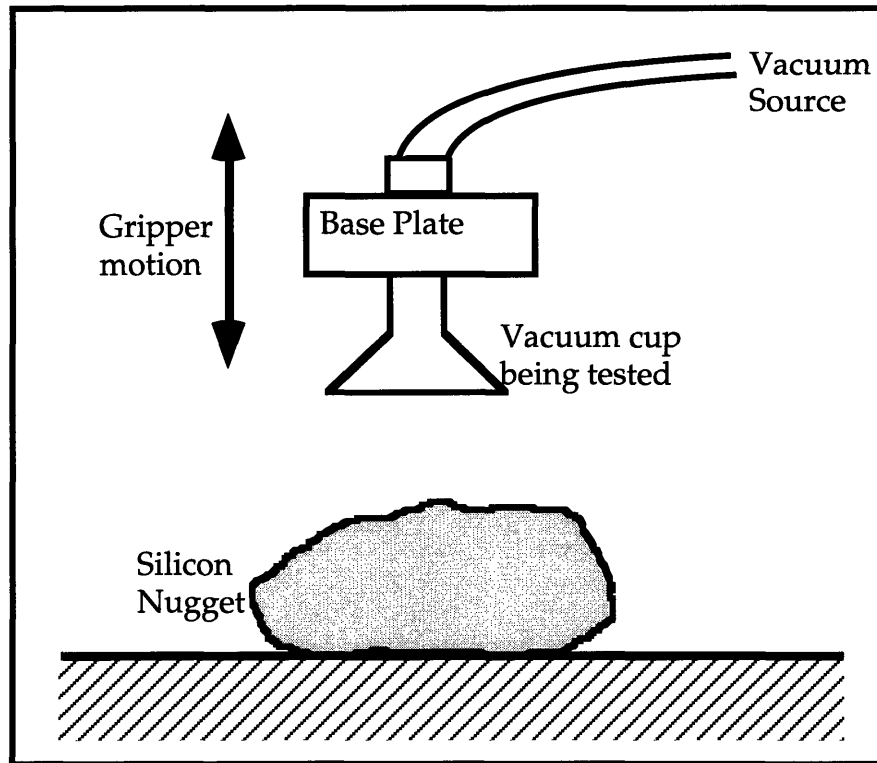


Figure 3-7: Vacuum Cup Testing Apparatus.

Vacuum cup selection test procedure

To evaluate a vacuum cup, the cup is manually brought down onto a nugget, and an attempt is made to grasp the nugget. The maximum vertical force is that which is necessary to fully longitudinally deflect the vacuum cup. The nugget is then released, and the procedure is repeated through ten trials on the same nugget with the vacuum cup at slightly different angles and positions relative to the nugget. The number of successful grasps for each cup on each nugget is recorded along with information regarding the quality of the grasp. Grasp quality data includes: firmness of hold, lifting force applied, and nugget features over which it is difficult to form a seal. Vacuum cup features that enhance or detract from grasping ability are also noted.

Vacuum cup selection test results

Except for the very small vacuum cups, which could not exert enough force to lift many of the nuggets, the grasping success of a suction cup was determined by the quality of the seal between the cup and the nugget. A poor seal did not allow the pressure differential necessary to grasp an object with a vacuum cup. Assuming constant vacuum pressure and air flow, variance in seal quality of a vacuum cup to an object's surface is determined by the object's surface texture, the vacuum cup geometry, and the vacuum cup compliance, rather than the vacuum pressure and air flow. The nugget surfaces to be grasped remained constant throughout the test, while the vacuum cup geometry and compliance varied for each cup.

Each of the 20 nuggets has a different surface texture, and each cup tested was used to grasp each of the nuggets. In general, particular nuggets would be most difficult to grasp for every vacuum cup tested. Similarly, some of the nuggets could be reliably grasped with almost every cup. The most difficult nuggets to grasp were those with very rough surfaces (pitted and scarred), those with sharp peaks (acute angles), and those with a characteristic mottled surface. In Figure 3-8, the first nugget has a rough, jagged surface, the second has sharp angles, and the third demonstrates a mottled surface texture.



(a) Top



(b) Side

Figure 3-8: Difficult to Grasp Nuggets, Top and Side Views

Vacuum cup geometry can be described using three criteria: first, by the shape of the lip of the cup, second, by the presence of cleats or other reinforcements in the cup, and third, by the depth of the vacuum cup. Cup lip shape had a noticeable effect on grasping success. A sharp edge was better able to adapt to the irregular surfaces of the nuggets. Flat or flared edges could not seal onto a nugget as well as a sharp edge. Illustrations of cup lips used in the test are in Figure 3-9(a).

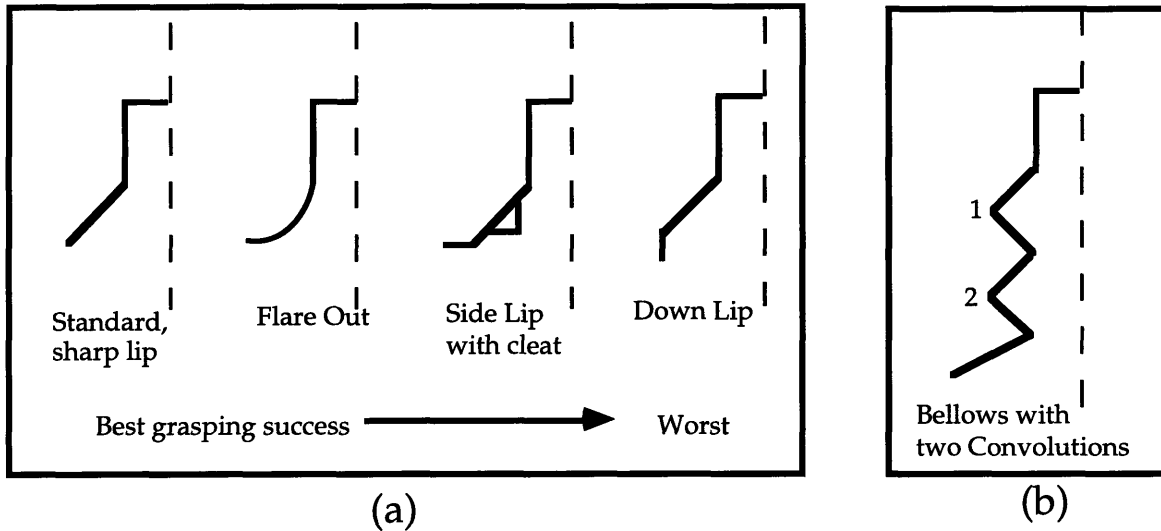


Figure 3-9: Vacuum Cup Lip Profiles

The presence of cleats had no noticeable effect on grasping success. Though cup depth had less of an effect on grasping than cup lip shape, shallow cups did not grasp nuggets as well as greater depth cups.

The vacuum cups tested were all made of vinyl of about the same wall thickness at an durometer of 45-50. Therefore, the compliance of a cup is determined by cup size and the presence of bellows (Figure 3-9(b)), rather than cup thickness and material stiffness. Cup compliance proved to be the most important factor for grasping success. Compliance allows the cup lip to adapt to surface irregularities and allows the cup to deform or rotate to accommodate angled surfaces or nugget edges. The larger cups could not adapt to sharp edges as well as smaller cups, but could grasp rough and mottled surfaces. Bellows greatly increased a cup's ability to adapt to uneven surfaces. A bellowed cup is able to tilt and attach to a surface that is up to 45° from horizontal.

Vacuum cup selection

The nugget grasping tests indicated that a bellowed, sharp lipped, non-shallow, smaller vacuum cup is the optimum cup. Cup size was further limited by lifting force; using the smallest cups would require a gripper with at least 10 cups in order to have enough force to lift the larger nuggets. VI-CAS vacuum cup model B3-1 (Figure 3-10) has three convolutions of bellows (the maximum number sold by VI-CAS), a sharp lipped and deep cup, and a diameter small enough to adapt to jagged surfaces but large enough to successfully lift all but the very largest of nuggets.

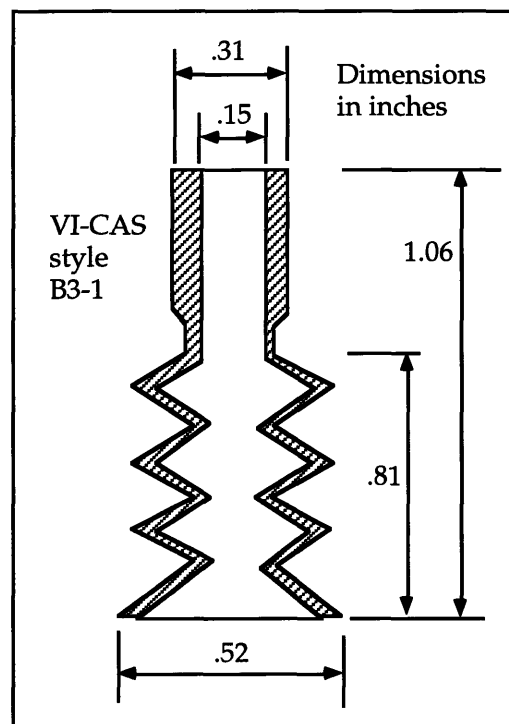


Figure 3-10: VI-CAS Vacuum Cup Model B3-1.

The B3-1 model was also the most successful cup of the tests, able to grasp 17 of the twenty nuggets on every trial and able to grasp the remaining three

nuggets 80% of the time. Nugget grasping test results using this vacuum cup in the proposed gripper design are presented in Section 4-3.

The final vacuum cup selection design issue was the determination of the number and spacing of cups used in the gripper. Due to its relatively small size, the B3-1 could not reliably lift the heaviest nuggets. Additionally, the compliance of the cup allowed a grasped nugget a large range of movement, making the nugget wobble with any gripper plate motion. Increasing the number of cups in the gripper from one to two provide the lifting force needed to grasp the largest nuggets, holds the nuggets more firmly, and can successfully grasp a greater number of nuggets (through cup redundancy). A three vacuum cup gripper can grasp a greater number of nuggets more securely than two cups, allows for a greater margin of error, and, when configured in a triangle, does not substantially increase the size of the gripper. (The gripper plate rotates; the circle described by three cups is only slightly larger than the circle described by two. Greater than three cups did not substantially improve gripper performance.) A triangular configuration of cups is stiffer than other configurations, resulting in a firmer hold by substantially reducing nugget wobble.

3.5.2 Gripper specifications

The gripper developed for the system is illustrated in Figure 3-11.

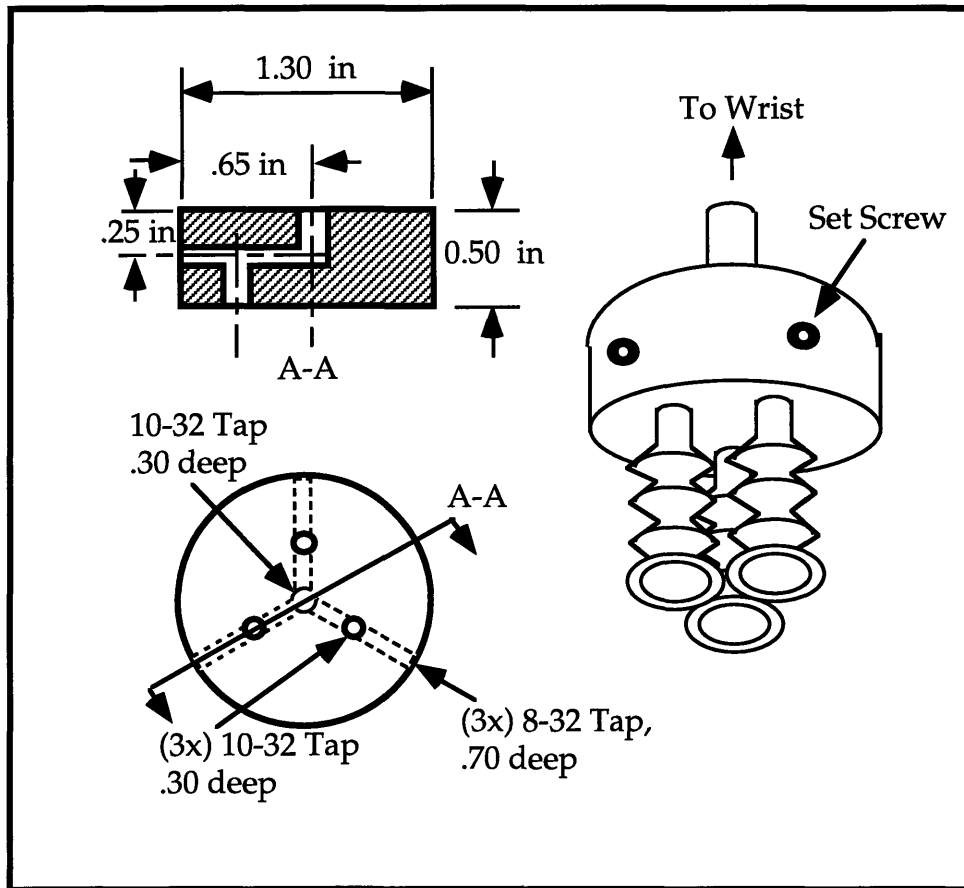


Figure 3-11: Gripper Design

The gripper features three closely spaced FDA grade vinyl B3-1 vacuum cups. The cups are attached to the gripper plate by three barbed pneumatic fittings (not shown). These fittings hold the cups securely while allowing easy replacement of worn or damaged cups. The cylindrical gripper plate also acts as a manifold. A single vacuum line enters the top of the plate and then separates to three channels to the vacuum cups.

Flow to each of the cups is regulated by three set screws in the manifold. The set screws act as tunable restriction valves by incrementally

closing off the air passage to the vacuum cups. The restrictions can be tuned so that the necessary pressure is maintained at each vacuum cup without severely restricting the air flow through each cup line. Without flow restriction in each vacuum cup line, a single unsealed cup would result in a loss of power (pressure) to the other cups. The restrictions allow the system to operate with one vacuum source entering the gripper plate, without a loss of power in the case of an unsealed cup. A description of the procedure to find the best tuned resistance in the gripper's air channels is in Section 4-2.

The need for the flow restriction would be alleviated if multiple vacuum lines from independent sources provided vacuum for each cup. A system where an unsealed cup's air flow is stopped with a valve would also prevent power loss in the system; such systems are described in (Lundstrom, 1977; Tella *et al*, 1982). However, the system described herein proved to be both simple and more than adequate for the grasping task, as illustrated in Section 4-3.

3.5.3 Pneumatic system design

The pneumatic system provides the gripper with the vacuum pressure and air flow needed to grasp nuggets. A schematic of the pneumatic system is shown in Figure 3-12. The system is powered by a rotary vane vacuum pump (specifications in appendix E). From the pump, the vacuum line runs through a three way, normally open solenoid valve that is operated through the RACS control computer. After the valve, the air line continues to the gripper plate manifold, described previously.

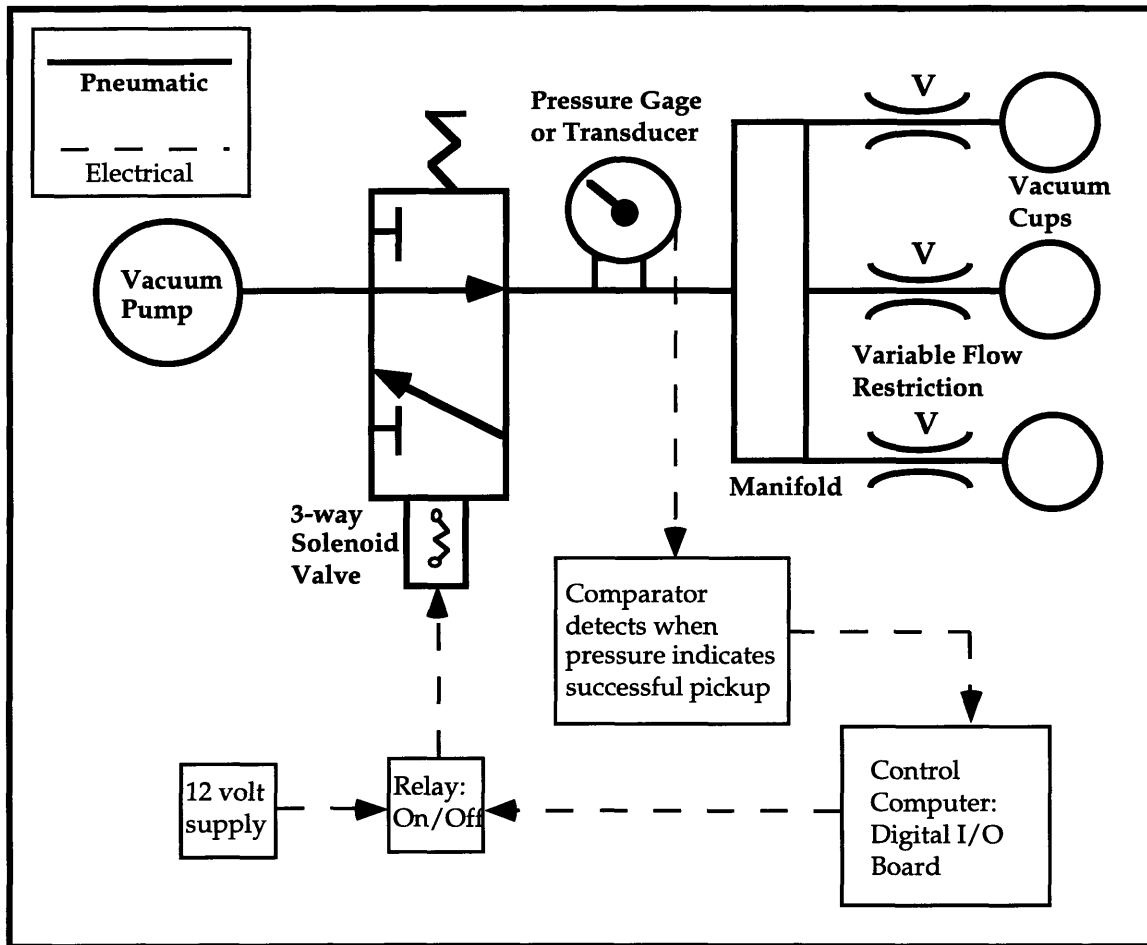


Figure 3-12: Gripper Pneumatic System Schematic

A pressure transducer can be added to the pneumatic lines to measure the vacuum pressure at a point just before the manifold. An Omega Model PX26 pressure transducer (Omega Engineering Inc., 1995) with a 1 atmosphere range is appropriate for the task. The vacuum pressure at the manifold point increases when an object is grasped by the gripper, and the output voltage of the pressure sensor varies linearly with pressure change. A comparator circuit can be used to detect when the voltage (pressure) passes a threshold that indicates a successful grasp. This information is then transferred to the system control computer.

3.6 Bulk filler design

Only the large (>80 grams) nuggets need to be individually placed in a crucible. There is no orientation or position requirement for the small (<80 grams) nuggets. Therefore, to minimize crucible packing time, it is desirable to place the small nuggets in the crucible in bulk. RACS process requirements specify that the bulk filling bin should hold at least 1 kg of silicon nuggets. The bulk filling bin should also securely carry the nuggets from a filling location to within the crucible. Once in the crucible, the nuggets should be gently released in a specified area. The material of the bulk filler must be appropriate for contact with polysilicon. A bulk filling bin that can be grasped and manipulated by the RACS end effector has been designed (Figure 3-13).

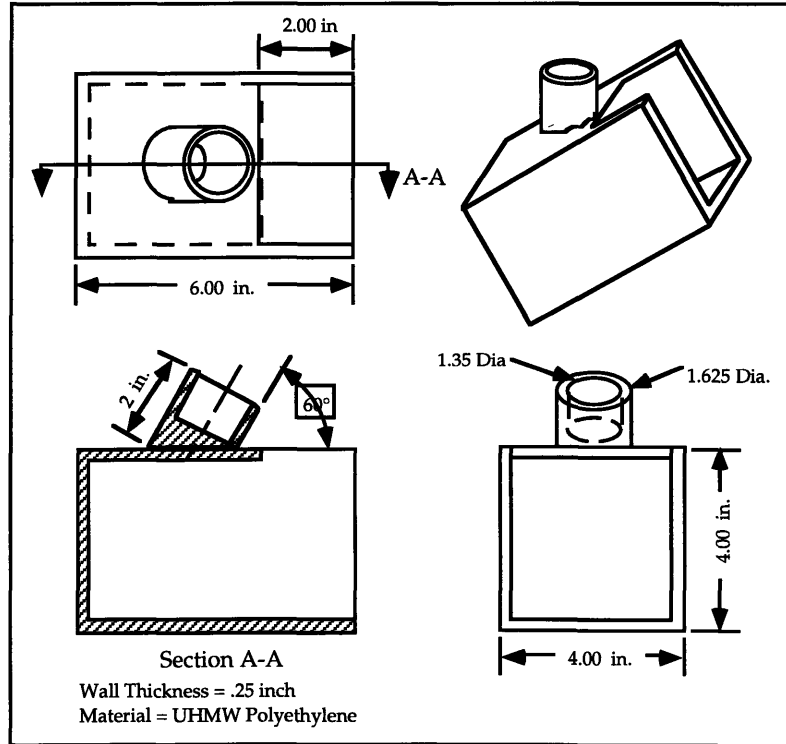


Figure 3-13: Bulk Filling Bin Design

The bin is a rectangular box 6" x 4" x 4" and rests in the bin filling area at a 30° angle with respect to the horizontal. Nuggets are loaded through the raised front opening. The vacuum gripper picks up the bin by inserting the gripper into a vertical, hollow cylinder and grasping its bottom. The gripper plate enters the cylinder along with the vacuum cups. The plate's diameter is slightly smaller than the interior diameter of the cylinder. The vacuum cups cannot bear the load of the bin and nuggets except to lift the bin. The cylinder transfers any torque or transverse loads to the gripper plate, which can bear the loads. To pour the nuggets into the crucible, the bin is rotated 60° by the wrist's first axis. Figure 3-14 is a picture of the bulk filling bin constructed for the demonstration system. The operation and fill properties of the bulk filling bin are described in Section 4-4.

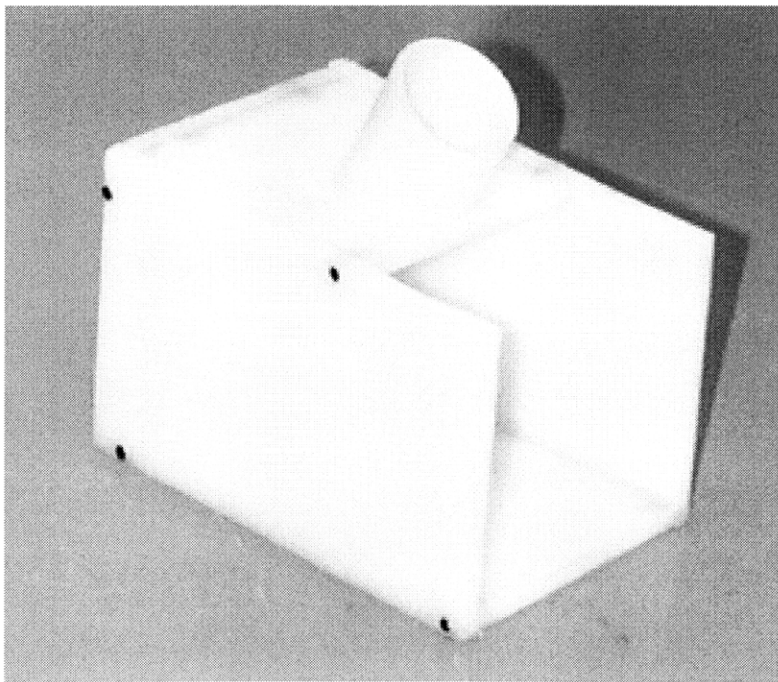


Figure 3-14: Photograph of the Bulk Fill Bin

The bin is made out of .25 inch thick ultra-high molecular weight polyethylene (UHMWPE). UHMWPE is used by SEH as a silicon contact surface, particularly as the table tops where nuggets are sorted by operators. UHMWPE does not contaminate the silicon by giving off chemicals (It is extensively used in the food industry for just this reason) and has a high impact resistance. PVDF and Teflon are also used as contact surface material, however UHMWPE proved to be better suited to the task due to its better machinability and lower cost.

Chapter 4

Nugget Grasping Performance

4.1 Introduction

This chapter describes the tests performed to optimize and characterize the operation of the RACS gripper and bulk filler. Section 4.2 describes the experiment completed to find the optimal manifold pressure for the gripper system. Section 4.3 gives the results of the tests performed to demonstrate the effectiveness of the gripper. The operation and usage of the bulk filling bin is described in Section 4.4. Section 4.5 summarizes and concludes the chapter.

4.2 Pressure and Air Flow Requirements

As described in Section 3.5.2, the gripper's manifold vacuum pressure must be tuned in order to maximize successful nugget grasps. Many times, only two of the cups will form a good seal onto a nugget, and the resulting power loss due to the unsealed cup must be minimized to ensure successful nugget grasps. The key to maximizing grasping ability is setting the manifold pressure such that nuggets can be lifted using just two of the three vacuum cups. The pressure is tuned by varying the flow resistance from the manifold

to each of the vacuum cups. High resistance minimizes power loss due to unsealed vacuum cups, while low resistance maximizes air flow through the cups, increasing the sealing ability of the cups. An experiment was performed to determine the optimal manifold pressure for the designed gripper.

Pressure test apparatus

The test to determine the best pressure was designed so that gripper motion in the test would mimic the vertical motion of a SCARA robot. The apparatus for the experiment is shown in Figure 4-1.

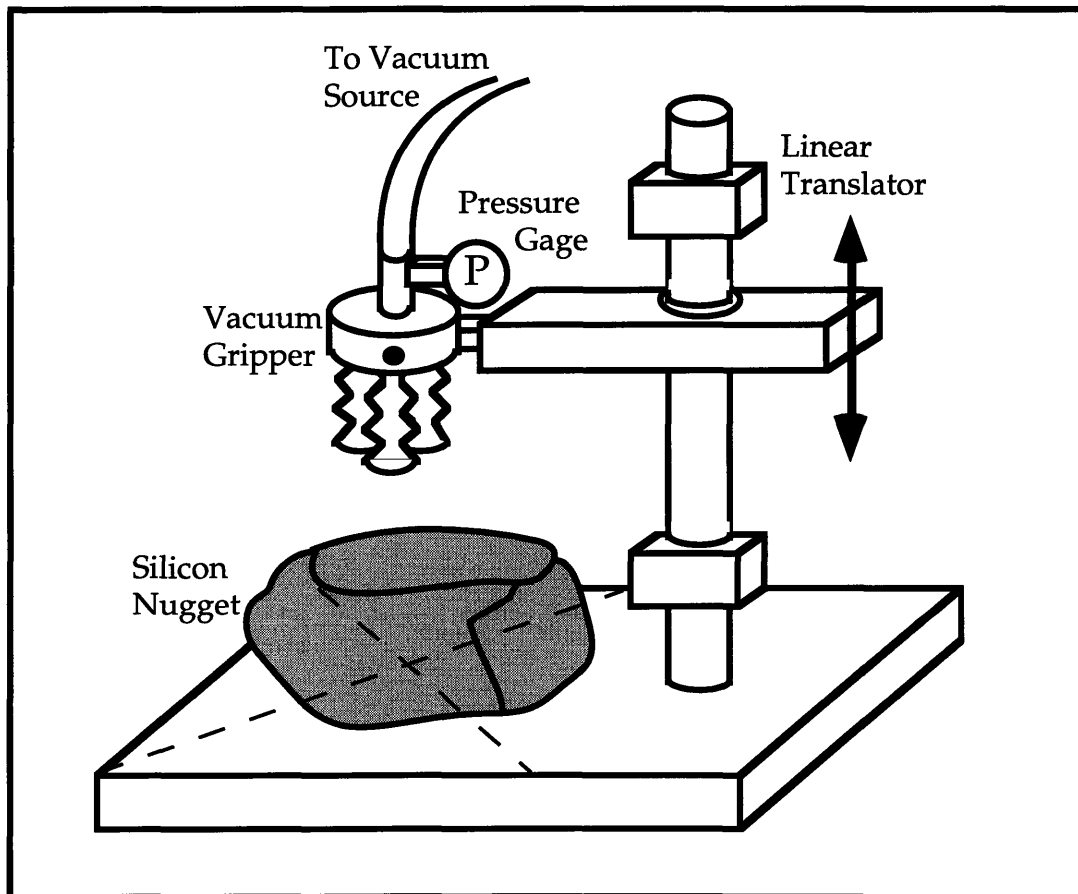


Figure 4-1: Manifold Pressure Experiment Apparatus

The prototype gripper was attached to a vertical linear translator and supplied with vacuum pressure. A vacuum pressure gage immediately prior to the

gripper manifold indicated the manifold pressure. A target directly beneath the gripper cups served as the placement location for the nuggets to be grasped. The twenty nuggets with potentially difficult to grasp surfaces from the vacuum cup selection experiment (Section 3.5.1 and Appendix D) were used in this experiment. Nuggets that are easy to grasp would be picked up at any pressure setting, and would add little useful information to the experiment.

Pressure test procedure

The grasping ability of the gripper was measured for a variety of manifold pressures by attempting to grasp each nugget five times using the vertical press apparatus. A maximum downward force of 15 N was used. To gage the ability of the gripper to grasp nuggets with only two sealed cups and one unsealed cup, one of the cups was removed from the gripper, and the grasping test procedure was repeated. One vacuum cup is not capable of successfully grasping very many nuggets, so experiments were not repeated with two unsealed cups and one open cup. The number of successful grasps and the firmness of the grasps were recorded for each nugget, for each pressure, and for the cases of three or two connected vacuum cups.

The manifold pressure of the gripper was measured when all three, two, one, and none of the cups were open. The datum pressure for the experiment was that of one open, unsealed vacuum cup, since this pressure indicates when a nugget can be successfully grasped with only two of the cups. High manifold pressures with unsealed lines mean that the flow resistance is

higher (less power loss) and that the air flow through the cup is lower. The manifold pressure was varied from the lowest resistance (maximum airflow) case to the highest resistance (minimum air flow) case. The flow resistance for a cup was tuned by sealing the other two cups and by adjusting the set screw of the open cup until the desired manifold pressure was reached. Figure 4-2 indicates how the manifold pressure varied for the four cup seal states while using the system's vacuum pump (Appendix E). Variations in vacuum source pressure will bias the y-axis scale.

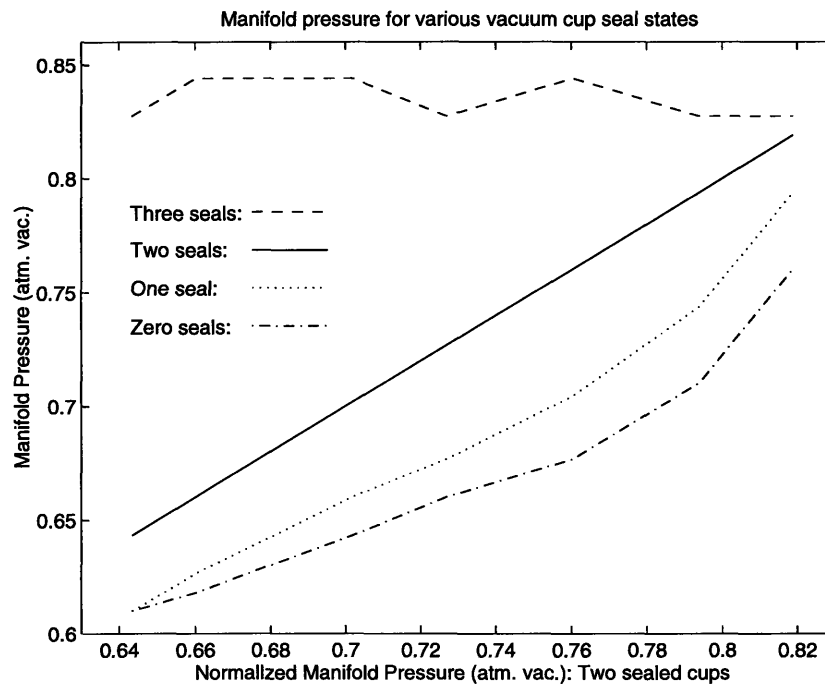


Figure 4-2: Manifold Pressure Variation During the Experiment

Pressure test results

The number of the twenty nuggets successfully grasped by the three cup gripper and the two cup, one open line gripper was recorded for seven different manifold pressures. The results of the experiment are given in Figure 4-3.

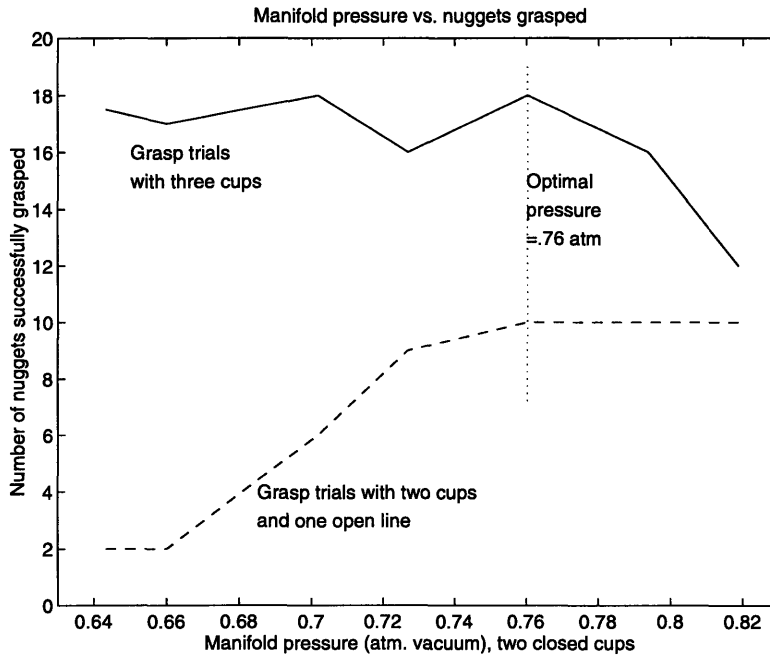


Figure 4-3: Pressure Test Results

The greatest number of nuggets was grasped at a vacuum pressure of .76 atmospheres. For low manifold pressures (low flow resistance), grasping was unsuccessful in the two cup trials because the unsealed vacuum cup power loss prevented enough pressure from being applied to the nuggets. For the three cup trials at low pressure, the loss of power for unsealed cups was balanced by higher air flow enhancing the ability of three cups to seal onto very rough surfaces of nuggets. At higher manifold vacuum pressures, the grasping performance for the three cup gripper fell due to low air flows decreasing sealing ability. The success of the two cup gripper at higher pressures peaks at ten nuggets because power loss is no longer significant and the maximum number of the difficult nuggets graspable by the two cup gripper has been reached.

4.3 Nugget Grasping Test Results

The operational parameters and grasping ability of the designed gripper were measured experimentally. First, the necessary downward grasping force was determined. Excessive downward forces could damage the gripper, while too little force would decrease grasping ability. Second, the grasping ability of the gripper was measured experimentally by attempting to grasp 309 nuggets above 80 grams in weight.

4.3.1 Grasping force experiment

The force with which the robot should press down upon a nugget when trying to grasp it was calculated by evaluating the properties of deflected vacuum cups. A B3-1 cup's bellows exhibits a linear spring constant of 180 N/m over 1.5 cm of travel. A cup can deform an additional .3 cm; however, the bellows no longer deforms linearly with force. A vacuum cup's bellows is fully deflected (1.8 cm) by 10 N (± 1 N) of force. An total of 20 N will cause a cup to bottom out, and additional load is taken by the barbed fitting holding the cup. The three cups of the gripper act as parallel springs, so load ratings add for each additional cup. A maximum downward grasping force of 15 N ensures that no cup will bottom out, while allowing the gripper to descend to nearly the maximum of 1.8 cm (approximately 1.7 cm for three equally deflected cups, the lowest deflection case for 15 N of force).

4.3.2 Nugget grasping test

The apparatus used to determine the manifold pressure (Figure 4-1) was also used for this experiment. The nuggets in the lab's sample which weigh more than 80 grams were gathered and used in the experiment. The nuggets were sorted as a RACS operator would, by manually selecting a nugget from a random state in a pile of nuggets and quickly placing the nugget so that its top surface is not obviously difficult to grasp. Difficult to grasp nugget features (described in 3.5.1) are easily identified after some exposure to silicon nuggets. After sorting, each nugget was placed on the nugget locating target to within ± 5 mm, with a random orientation about the nugget's vertical axis. The gripper, with the manifold vacuum pressure tuned to .76 atmospheres, is then brought down onto the nugget without bottoming out any of the vacuum cups. The nugget was then lifted, and the number of vacuum cups holding it and the firmness of the grasp was recorded. A firm grasp was one in which the nugget could be jarred and not fall from the gripper. If the nugget was not grasped with the first attempt or if only one cup held the nugget, the procedure was repeated for a second time after moving the nugget 10 mm in a random direction. If the second grasp failed, a third grasp was attempted after moving the nugget 10mm perpendicular to the first movement. Data were recorded for each of the 309 nuggets.

The gripper grasped 90.9% of the nuggets in one attempt and 98.1% in two grasping attempts. In no trials did a third grasping attempt pick up additional nuggets. Test results are summarized in Table 4-1.

Table 4-1: Grasping Test Results for 309 Nuggets

Grasping attempt	3 cup grasp	2 cup grasp	Total successes	1 cup grasp	Total failures
First	67.3%	23.6%	90.9%	6.8%	9.1%
Second (cumulative)	69.9%	28.2%	98.1%	1.0%	1.9%

Nuggets held with two or three cups can be manipulated by the RACS robot and are thus considered successful grasps. A two cup grasp was as firm as a three cup grasp for similarly sized nuggets in all trials but for the trials with the largest nuggets. The largest nuggets do not rotate with gripper plate rotation due to insufficient stiffness of a two cup grasp. Grasps with only one cup do not hold a nugget firmly enough to be safely manipulated, so are considered failed grasps. Additionally, the pressure change at the gripper manifold was very low for one cup grasps, making detection of the grasps without use of the end effector force/torque sensor difficult.

During the experiment, nine of the 309 nuggets to be grasped were identified as having surfaces that the gripper would have trouble grasping. Five of the six nuggets that could not be grasped were from this group. Three of the ungrasped nuggets had a highly mottled surface texture, two had rough and steep surfaces, and one had a very rough top surface.

The three vacuum cups were in good condition after the grasping tests. They were coated with a thin layer of silicon dust. The dust did not seem to effect the performance of the gripper. The accumulation of dust indicates that a filter is needed in the pneumatic system to remove the silicon dust and particles. The cups exhibited minimal wear and tear. One cup had a pin hole in a lip, another's edge was a bit ragged, and one of the bellows had a small crack on the outside of it. Most of the damage can be attributed to the rough handling, such as ripping a nugget off of the gripper without first releasing the vacuum pressure, that the cups experienced during the test. The cups proved to be robust more extreme under conditions than would be experienced in a RACS.

The success rates of the gripper could be improved by increasing the compliance of the vacuum cups, both in bellows travel and cup softness. However, increasing the compliance much more than the current compliance would decrease the firmness of the nugget grasps, for the cups would deform too easily under loads. Power loss due to unsealed vacuum cups was only a factor in one or possibly two of the grasping failures, so decoupling the vacuum sources would only increase the performance of the gripper by 1%.

4.4 Bulk Filling Operation

The bulk fill bin is used to transport and release nuggets into the crucible in bulk. For the demonstration system, a bin that can hold 1 kg of nuggets was constructed. Figure 4-4 depicts how the bin is located within an 18" crucible.

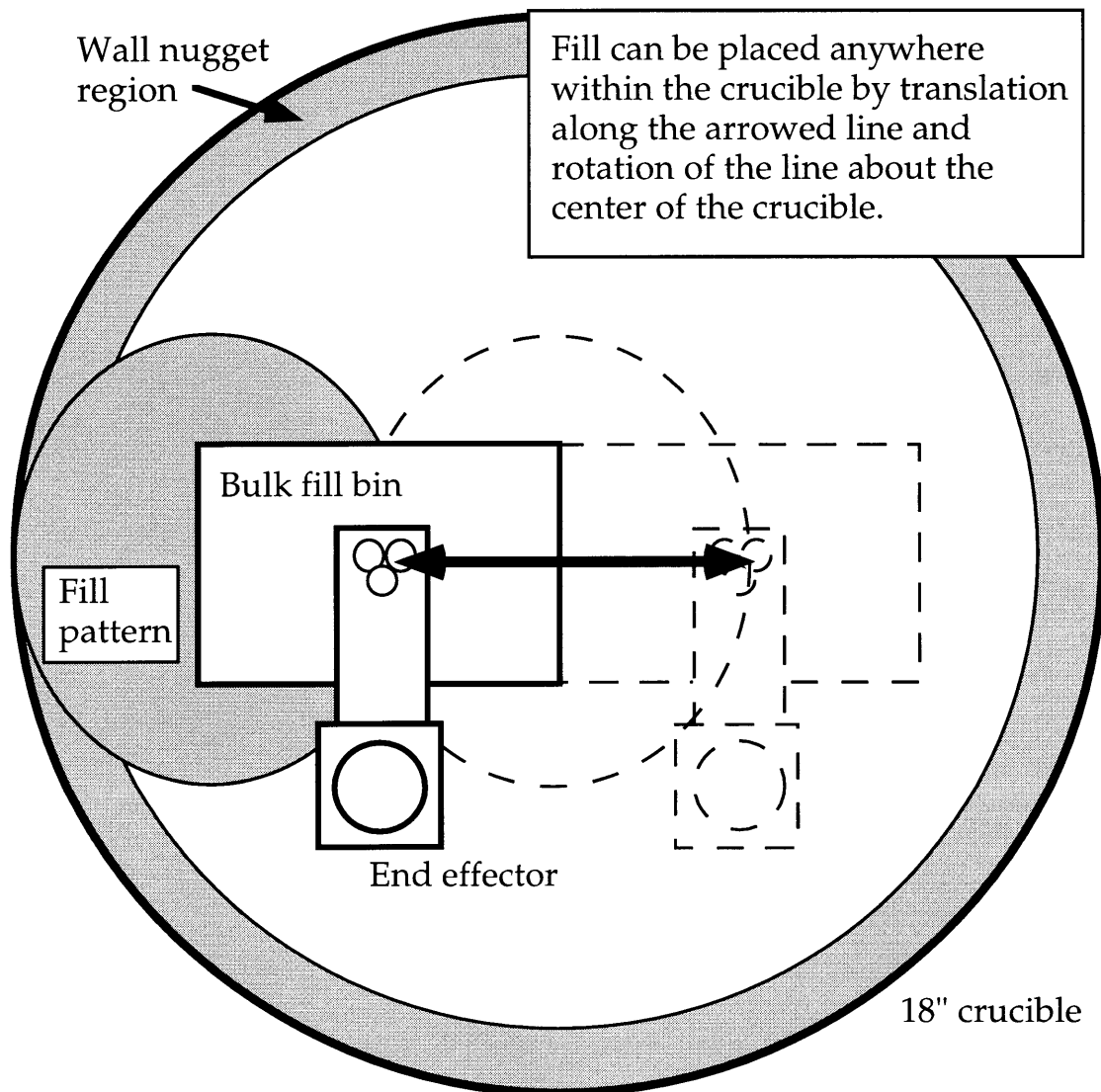


Figure 4-4: Bulk Filling Regions within an 18" Crucible

The bin load size should be maximized in order to decrease total crucible filling time. The size of the bin is constrained by the size of the crucible in

which it must operate. The 6"x4"x4" bin holds 1 kg of nuggets and fits comfortably within an 18" crucible. The bulk fill bin is grasped and manipulated by the RACS end effector. Figure 4-5 illustrates the bulk filling process.

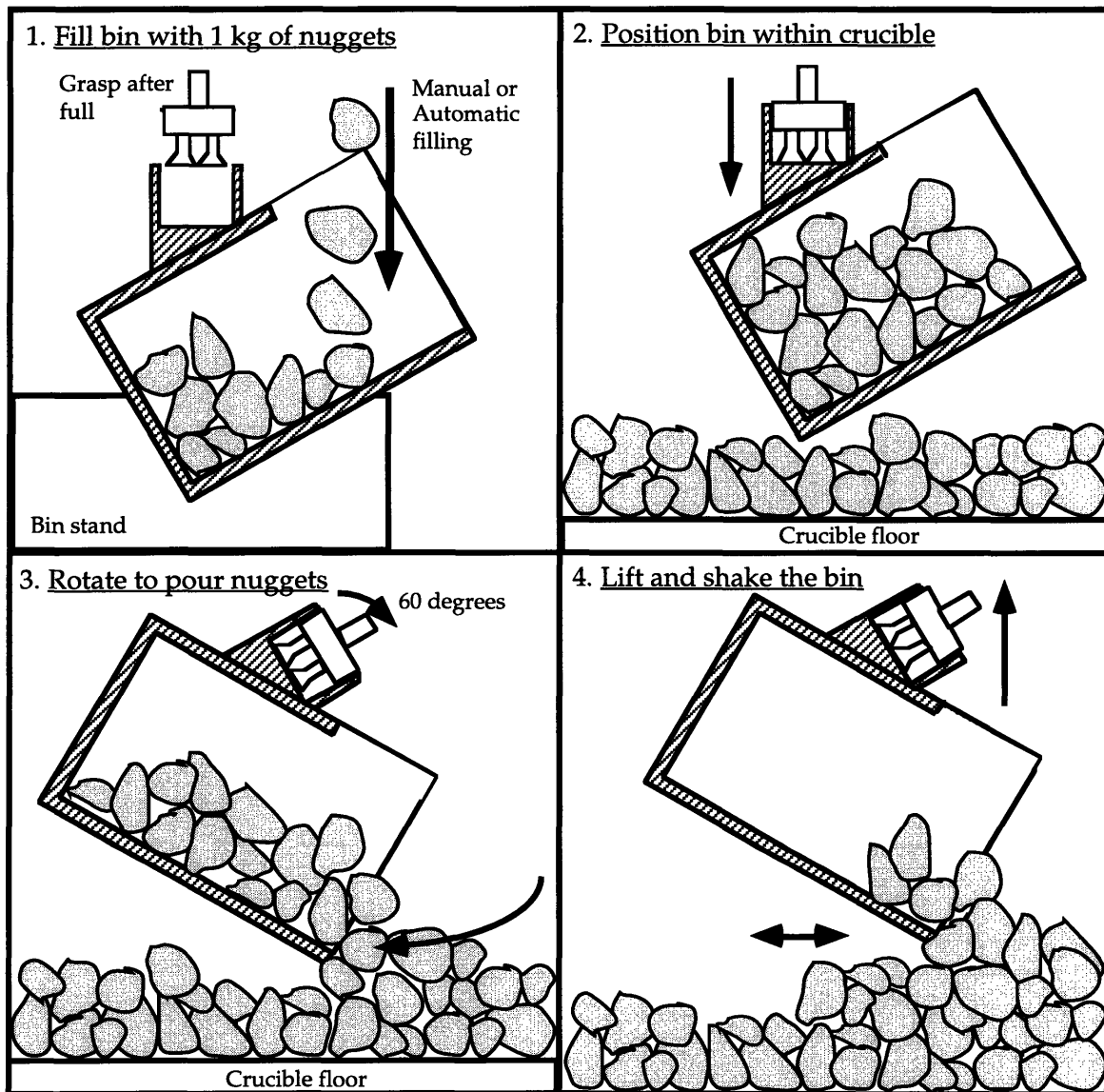


Figure 4-5: Bulk Filling Operation

The bulk filling bin rests in a stand in a filling area at a 30° angle to the horizontal. Nuggets are placed within the bin either manually or from a bulk

transport conveying system. When the bin is full, the end effector's gripper descends into the cylinder of the bin, and the bin is carried to the crucible. The bin is lowered in the crucible to a location such that, after rotation wrist joint two rotation, the nuggets would pour into the desired area. The bottom edge of the bin is located at the top level of the nuggets already in the crucible. This current fill level is known approximately from vision system data and can be determined by touching the fill level nuggets with the bottom of the bulk fill bin and detecting contact with the wrist force sensor. Once lowered to the desired location, the bin is rotated 60° at 1 revolution per second by the first joint of the wrist. Nuggets now pour into the crucible. The bulk fill bin is lifted vertically at 20 mm/s and shaken with an amplitude of approximately 2° at 4 Hz to release the remaining nuggets into the crucible. Approximately 8 cm of vertical travel is needed to fully empty a bin. If necessary, the bin can be positioned horizontally and pressed against the top layer of nuggets to smooth and settle the nuggets. Downward force of 10 N seems to be appropriate for smoothing. When the bin is empty, the wrist returns to its home position, and the bulk fill bin is returned to the filling station.

Preliminary tests to demonstrate the end effector manipulating the bin were performed. A filled bin was moved through the required filling motions with the robot and end effector, and bulk fill nuggets were successfully poured. Figure 4-6 depicts a front and side view of the bulk filling process just as nuggets begin to pour from the bin.

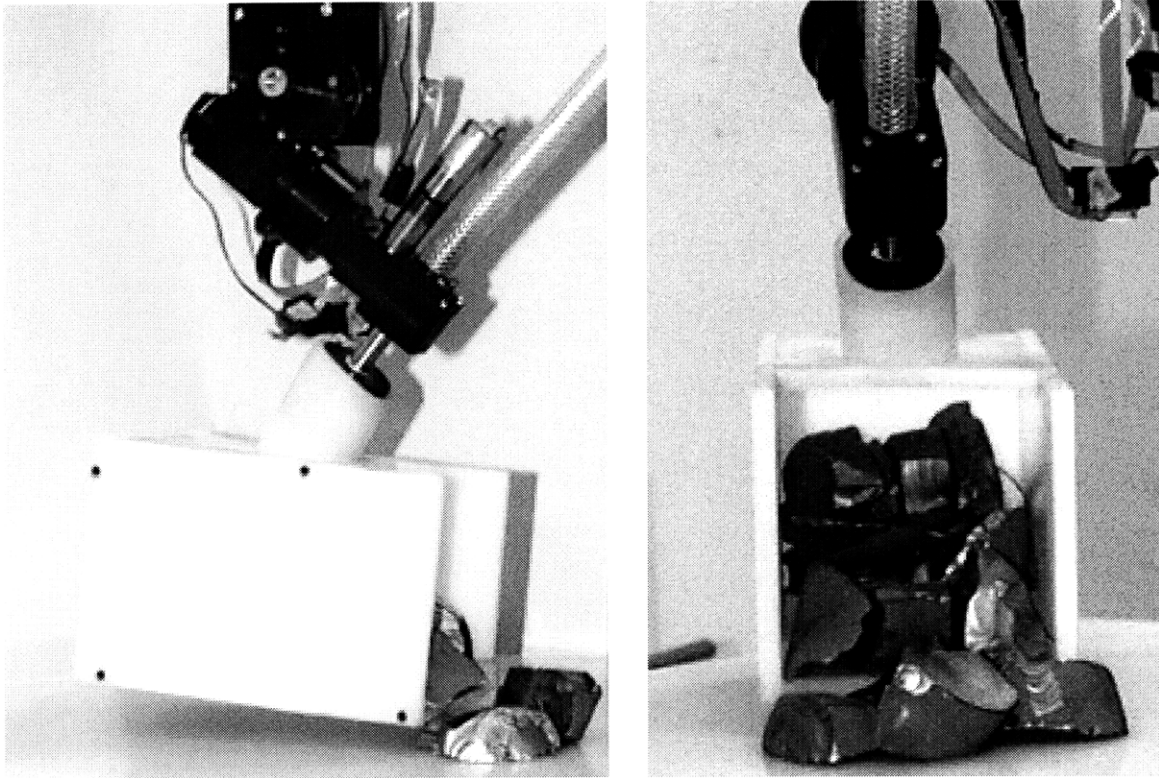


Figure 4-6: Bulk Fill Pouring Using the End Effector

The size and shape of the pour pattern created by a bulk filling operation is useful for determining bulk filling locations during RACS operation. Nuggets were poured onto a flat surface and onto a leveled layer of previously placed nuggets to determine the size and shape of the pile formed when nuggets are poured using the designed bulk fill bin. The flat surface simulates the bottom of the crucible during bed formations. Figure 4-7 illustrates the results of the test.

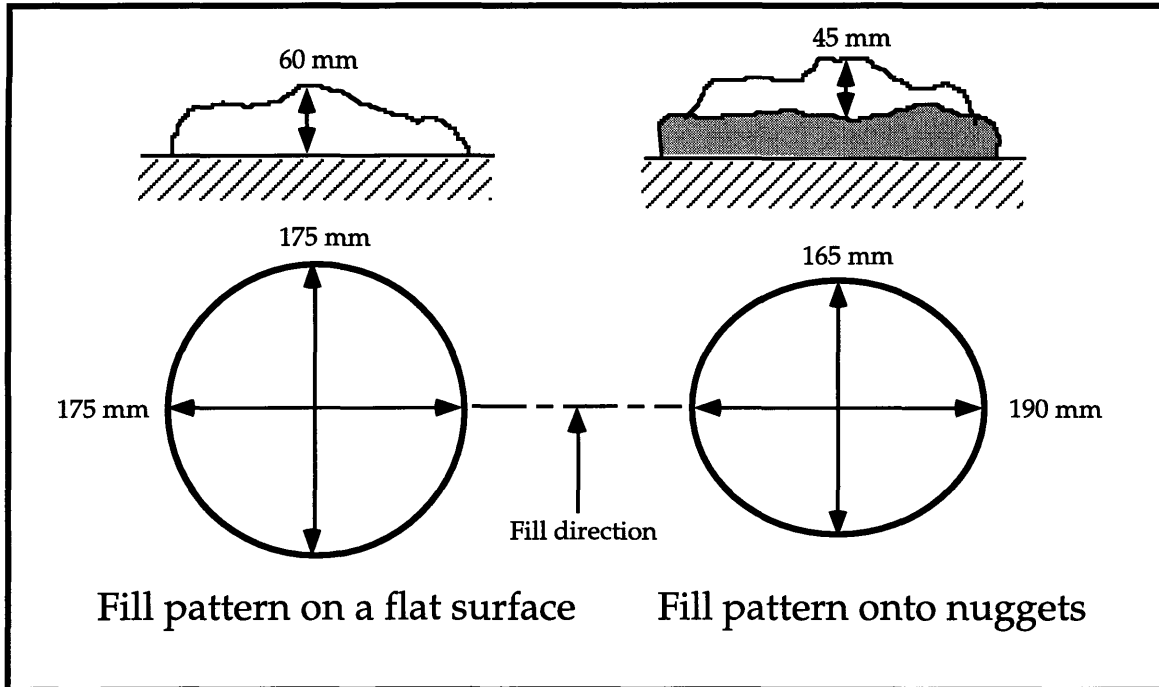


Figure 4-7: Bulk Filling Pour Pattern

During the pouring test, the bin was filled with between 0.9 and 1.1 kg of small nuggets. The average weight of the nuggets used was 41 grams. The nuggets filled from 2/3 to 3/4 of the bin. Filling a bin more than 3/4 full risks nuggets falling out of the bin or becoming jammed inside of the bin. Pouring onto a flat surface tended to produce a circular top view, while pouring onto a nugget bed produces ellipses with the minor axis in the direction of filling. The height of the layer poured onto nuggets was less due to nuggets filling in voids of the bed layer.

The coefficients of friction for polysilicon nuggets against UHMWPE varies from nugget to nugget (due to irregular crystal structure and surface texture effects.) The coefficient of sliding friction was experimentally determined to be $.22 \pm .02$, and the coefficient of static friction is $.27 \pm .02$.

4.5 Conclusions and Summary

The manifold pressure that allowed the most nuggets to be successfully grasped was determined experimentally. A manifold vacuum pressure of .76 atmospheres for the designed gripper system maximized grasping ability. Using this manifold pressure, the gripper was able to successfully grasp 98.1% of the large nuggets in up to two grasping attempts. Nuggets that are not easily grasped are identifiable, and can be used instead as bulk fill material. The bulk fill bin developed for the 18" crucible holds 1 kg of nuggets and can release the nuggets within a designated area anywhere within a crucible. The bulk filling procedure produces repeatable nugget patterns, aiding in the determination of bulk placement locations.

Chapter 5

Conclusions

5.1 Contribution of this Thesis

This thesis has described the development of an end effector system that can grasp and manipulate irregularly shaped objects in an industrial setting. A description of the industrial setting has given along with the characteristics of the irregular objects to be grasped. The Robot Assisted Crucible Charging System that includes the end effector is also described. The design of the end effector system is presented, followed by experimental results on the operation of the end effector.

The end effector design challenge of the thesis was to grasp a high percentage of irregularly shaped polysilicon nuggets. The parameters of the problem limited the solution to a vacuum gripper. The selection of an Adept One SCARA robot in the demonstration system required the design of specific end effector components to make up for the robot's limitations. An air cylinder stroke extension allows the entire depth of the crucible to be reached,

while a three degree of freedom wrist provides the range of nugget orientations required by the RACS.

The grasping ability of a range of vacuum cups was tested to determine the vacuum cup size, shape, and configuration that would maximize nugget grasping success rate. Nugget surface features which influenced cup grasping ability were also noted. A vacuum cup that demonstrated the desired cup characteristics was found and used in the end effector's gripper.

To permit the use of a single vacuum source for the gripper, the pressure supplied to the gripper was regulated at the gripper manifold. A simple, pressure regulating design integral to the gripper manifold was presented. The manifold vacuum pressure that maximized nugget grasping ability for the gripper system was determined experimentally.

The grasping capability of the gripper was demonstrated by attempting to grasp a large number of nuggets. The results of the tests indicated that the designed gripper can perform its required task effectively.

The end effector and its vacuum gripper grasp and manipulate the bulk filling bin developed to pour nuggets into a crucible. The use of the bulk filling bin is illustrated, and the characteristics of its operations are described.

5.2 Application to the Factory System Design

One purpose of this thesis was to demonstrate a portion of the technology required for a RACS factory system. To illustrate the proposed factory RACS, an overhead view of the concept for the factory system is

depicted in Figure 5-1 and a side view of the same system is in Figure 5-2. Details of the factory system and its advantages can be found in (Dubowsky, 1997).

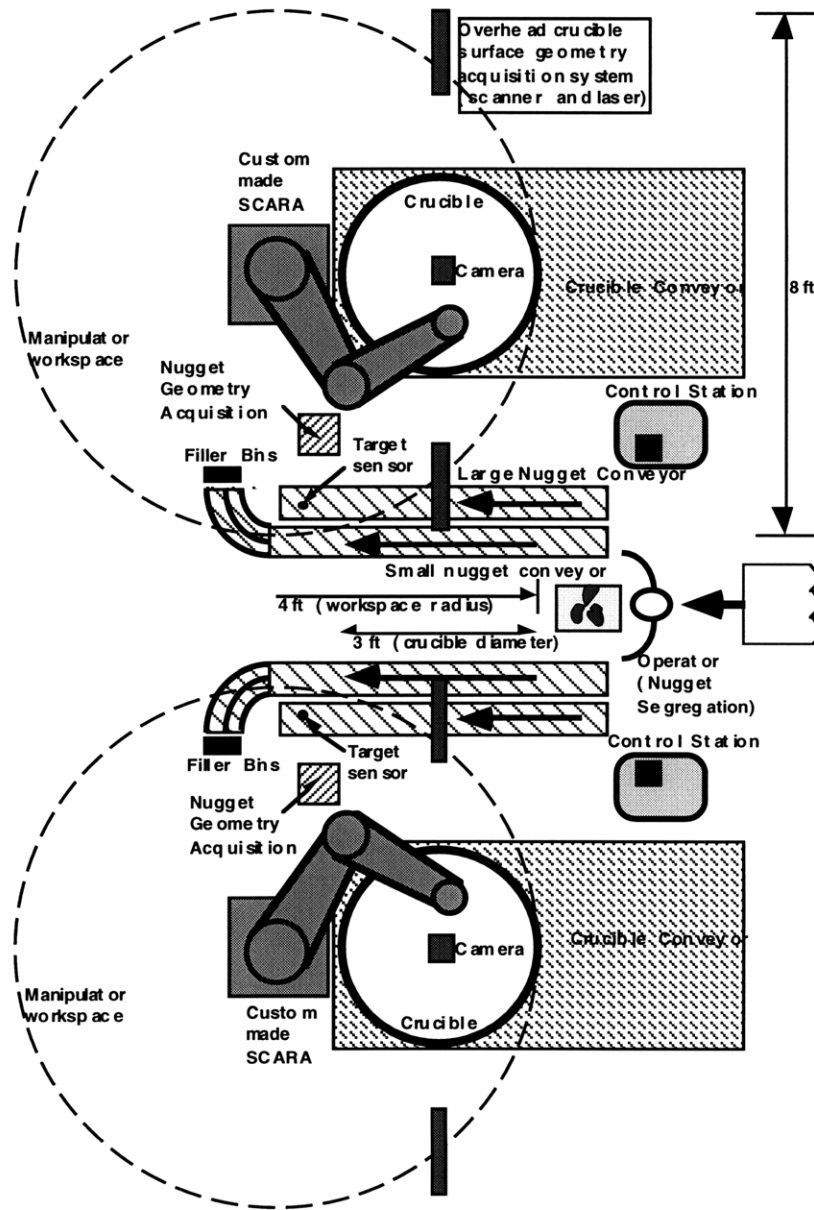


Figure 5-1: Overhead View of the Factory RACS

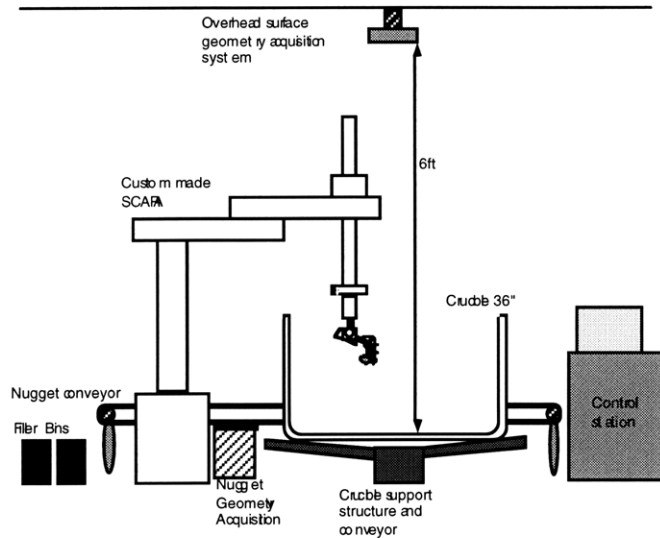


Figure 5-2: Side View of the Factory RACS

Only the gripper and its associated pneumatic system would be used in the factory system. The force sensor, stroke extension, and wrist should be customized for the specific robot used in the factory RACS or be integral to a customized robot designed for the factory RACS. Though independent vacuum sources for each cup would not substantially increase the grasping ability of the gripper, such a system would simplify the pneumatic design and eliminate the need for regulating and maintaining the tuned pneumatic system. The vinyl vacuum cups proved to be robust and wear resistant and are easy and inexpensive to replace if necessary.

The size of the bulk filling bin can be increased for usage in the larger (36") crucibles in the factory RACS. The volume of the bulk filling bin can be at least doubled. The actual maximum size of the bin depends upon the joint configuration and payload of the robot used in the factory RACS.

5.3 Suggestions for Further Work

The stroke extension system and gripper pressure sensor system have yet to be constructed and tested within the end effector system. Further work would be to complete the system. The nugget grasping test can also be repeated using a complete RACS demonstration system to further validate the grasping ability of the end effector. Tests using the RACS demonstration system can lead to continued optimization of the end effector design.

This thesis describes the development of a gripper that can grasp irregular objects in a specific industrial setting. The developed gripper is readily customizable for other applications, which should be explored. Much work has been done on grasping regularly shaped objects with irregular positions and orientations, mostly using vision systems. However, little work has been done on grasping highly irregularly shaped objects. Further development of systems to grasp such objects would advance the state of gripper technology.

The vacuum gripper described in this thesis is highly tolerant to object irregularity in shape and uncertainty in position. The design is applicable to any task where adaptability in the presence of little information about an object to be grasped is desired. Only rough mechanical positioning is required to grasp an object. The exploration of the adaptability of the design is a field for further work.

References

- Adept Technology Inc., San Jose, CA. *Technical Specifications Bundling, February 1997*. 1997.
- Avallone, E.A. and Baumeister, T. (Eds.) *Marks' Standard Handbook for Mechanical Engineers*, 10th Edition. McGraw-Hill, New York. 1996.
- Bach, J., Herard, S., Hermann, J.P., Michard, G., and Pardo, P. "Bin-picking using a 3-D sensor and a special gripper." *Proceedings of the 5th International Conference on Robot Vision and Sensory Controls*, pp: 529-540. October 1985.
- Bianchi, G. and Rovetta, A. "Grasping Process for Objects of Irregular Shape." In *Robot Grippers*, D.T. Pham and W.B. Heginbotham (Eds.), pp: 125-137. Springer-Verlag, NewYork. 1986.
- Calzaretta, J. *Delicate Manipulatioin of Irregularly-shaped Rigid Objects in a Stiff, Fragile Environment*. S.M. Thesis, Department of Mechanical Engineering, Massachusetts Institute of Technology, Cambridge, USA. June 1998.
- Cutkosky, M. *Robotic Grasping and Fine Manipulation*. Kluwer Academic Publishers, Boston. 1985.
- Dietze, W., Keller, W., and Mühlbauer, A. "Float-Zone Grown Silicon" in *Crystals, Growth and Applications, Vol. 5*, J. Grabmaier (Ed.) pp: 6. Springer-Verlag, New York. 1981.
- Dubowsky, S. "Robot Assisted Crucible Charging System, Year two progress report." MIT Internal Report. December 1997.

- Fabco-Air, Gainesville, FL. *Global Series® Air Cylinders*, Catalog. 1996.
- Fan Yu, C. "Gripping Mechanisms for Industrial Robots: An Overview." *Mechanism and Machine Theory* , 17(5), pp: 299-311. 1982.
- Garcia-Rubio, P. *Gripper Design for the Robot Assisted Crucible Charging System*. S.B. Thesis, Department of Mechanical Engineering, Massachusetts Institute of Technology, Cambridge, USA. June 1997.
- Gast Manufacturing Corporation, West Hartford, CT. *Gast® Vacuum Pumps*. Catalog. 1992.
- Goldenberg, A.A., Apkarian, J.A. and Smith, H.W. "An Approach to Adaptive Control of Robot Manipulators Using the Computed Torque Technique." *ASME Journal of Dynamic Systems, Measurement, and Control*, Vol. 111, pp: 1-8. 1989.
- Gorce, P. and Fontaine, J.G. "Design Methodology Approach for Flexible Grippers." *Journal of Intelligent and Robotic Systems*, 15 pp: 307-328. 1996.
- Hautau, L. and DiPietro, F. "Planning Robotic Production Systems." In *Handbook of Industrial Robotics*, S. Nof (Ed.) John Wiley and Sons, New York. pp: 691-721. 1985.
- Holzbock, W.G. *Robotic Technology, Principles and Practice*. Van Nostrand Reinhold Company Inc., New York. 1986.
- JR³ Inc, Woodland CA. *JR³ Universal Force-Moment Sensor System Operation Manual*. 1988.
- Karakerezis, A., Ippolito, M., Doulgeri, Z., Rizzi, C., Cugini, C., and Petridis, V. "Robotic Handling for Flat Non-Rigid Materials." *Proceedings of the 1994 IEEE International Conference on Systems, Man and Cybernetics*, Vol 1, pp: 937-946. 1994.

- Kato, I. and Sadamoto, K. *Mechanical Hands Illustrated*. Springer-Verlag, Berlin. 1987.
- Kolluru, R., Valavanis, K.P., Steward, A., and Sonnier, M. "A Flat-Surface Robotic Gripper for Handling Limp Material." *IEEE Robotics & Automation Magazine*, 2(3) pp: 19-26. September 1995.
- Lundstrom, G., Glemme, B., and Rooks, B.W. *Industrial Robots - Gripper Review*. International Fluidics Services, LTD. Bedford, England. November 1977.
- Mannaa, A.R., Akyurt, M., and El-Kalay, A.K. "Enhanced Gripping Mechanisms for Industrial Robots." *International Journal of Robotics and Automation*, 6(3) pp: 156-160. 1991.
- Mason, M.T. "Manipulator Grasping and Pushing Operations." In *Robot Hands and the Mechanics of Manipulation*. MIT Press, Cambridge, USA. 1985.
- Meyer, J. "An Overview of Fabrication and Processing Applications." In *Handbook of Industrial Robotics*, S. Nof (Ed.) John Wiley and Sons, New York. pp: 807-820. 1985.
- Micallef, R. "An Overview of Vacuum and Gripper End Effectors." *Robotics Engineering*, 8(2) pp: 5-8. February 1986.
- Mirco Mo Electronics, Inc. *Micro Mo DC Motor Catalog*. 1996.
- Neal, M.J. Rowland, J.J., and Lee, M.H. "A behaviour-based approach to robotic grasp formulation: experimental evaluation in a food product handling application." *Proceedings of the 1997 IEEE ICRA*, Albuquerque, NM, pp: 304-309. April 1997.
- Nevins, J. and Whitney, D. "Computer Controlled Assembly." *Scientific American*, 238(2) pp: 62-74. February 1978.

- Nice, Travis, SEH America Process Engineer. Personal Correspondances. October 1997 - March 1998.
- Omega Engineering Inc, Stamford CT. *The Pressure, Strain, and Force Handbook*. 1995.
- Perovskii, A.P. "Universal Grippers for Industrial Robots." In *Robot Grippers* D.T. Pham and W.B. Heginbotham (Eds.) pp: 79-84. Springer-Verlag, NewYork. 1986.
- Potter, R. "End of Arm Tooling," In *Handbook of Industrial Robotics*, S. Nof (Ed.) John Wiley and Sons, New York. pp: 775-787. 1985.
- Rehg, J.A. *Introduction to Robotics in CIM Systems*. Prentice-Hall, Inc., New Jersey. 1997.
- Salisbury, J.K. "Kinematic and Force Analysis of Articulated Hands." In *Robot Hands and the Mechanics of Manipulation*. MIT Press, Cambridge USA. 1985.
- Scott, P.B. "The 'Omnigripper': A Form of Robot Universal Gripper" In *Robot Grippers*, D.T. Pham and W.B. Heginbotham (Eds.) pp: 109-123. Springer-Verlag, NewYork. 1986.
- SEH America Web Site: www.sehamerica.com
- Shackelford, J.F., Alexander, W., and Park, J.S. (Eds.) *CRC Materials Science and Engineering Handbook, 2nd Edition*. CRC Press, Cleveland. 1994.
- Shimoga, K.B. "Robot Grasp Synthesis Algorithms: A Survey." *The International Journal of Robotics Research*, 15(3) pp: 230-266. June 1996.
- Stansfield, S.A. "Robotic Grasping of Unknown Objects: A Knowledge-based Approach." *The International Journal of Robotics Research*, 10(4) pp: 314-326. August 1991.

- Sujan, V. *Sensor Based Manipulation of Irregularly Shaped Objects with Special Application to Semiconductor Industry*. S.M. Thesis, Department of Mechanical Engineering, Massachusetts Institute of Technology, Cambridge, USA. June 1998.
- Tanie, K. "Design of Robot Hands." In *Handbook of Industrial Robotics*, S. Nof (Ed.) John Wiley and Sons, New York. pp: 112-137. 1985.
- Tella, R., Birk, J., and Kelley, R. "General Purpose Hands for Bin-Picking Robots." *IEEE Trans. on Systems, Man, and Cybernetics*, Vol SMC-12(6) pp: 828-837. 1982.
- Tella, R. and Birk, J. "A Contour-Adapting Vacuum Gripper." In *Robot Grippers*, D.T. Pham and W.B. Heginbotham (Eds.) pp: 85-100. Springer-Verlag, NewYork. 1986.
- Trobina, M. and Leonardis, A. "Grasping Arbitrarily Shaped 3-D Objects from a Pile." *Proceedings - IEEE International Conference on Robotics and Automation*, Vol 1 pp: 241-246. May 1995.
- VI-CAS Manufacturing, Cincinnati, OH. *Super Cup Catalog*. 1997.
- Whitney, D. "Planning Programmable Assembly Systems." In *Handbook of Industrial Robotics*, S. Nof (Ed.), John Wiley and Sons, New York. pp: 1031-1053. 1985.
- Whitney, D. "Real Robots do need jigs." *Harvard Business Review* 64(3), pp: 110-115. May-June 1986.
- Wolf, T. and Tauber, R.N. *Silicon Processing for the VLSI Era, Volume 1: Process Technology*. Lattice Press, Sunset Beach CA. 1986.
- Wright, P. and Cutkosky, Mark. "Design of Grippers." In *Handbook of Industrial Robotics*, S. Nof (Ed.), John Wiley and Sons, New York. pp. 96-111. 1985.

Zesch, W., Brunner, M., and Weber, A. "Vacuum Tool for Handling Microobjects with a Nanorobot." *Proceedings of the 1997 IEEE ICRA* Albuquerque, NM, pp: 1761-1766. 1997.

Appendix A

Adept One Specifications

The technical specifications of the Adept One robot used in the laboratory demonstration RACS are presented in Table A-1, (from Adept Technology Inc., 1997). The dimensions of an Adept One robot are shown in Figure A-1. The workspace of an Adept One is illustrated in Figure A-2. The base mounting dimensions are depicted in Figure A-3. The end user flange for the robot is shown in Figure A-4. (All figures are from Adept Technology Inc., 1997).

Table A-1: Adept One Specifications

Payload:	9.09 kg (20 lbs)
Downward force:	18.2 kg (40 lbs)
Repeatability (X,Y):	.025mm (.001 in.)
Joint 1 range:	300°
Joint 2 range:	294°
Joint 3 stroke:	195mm (7.7 in)
Joint 4 range	554°

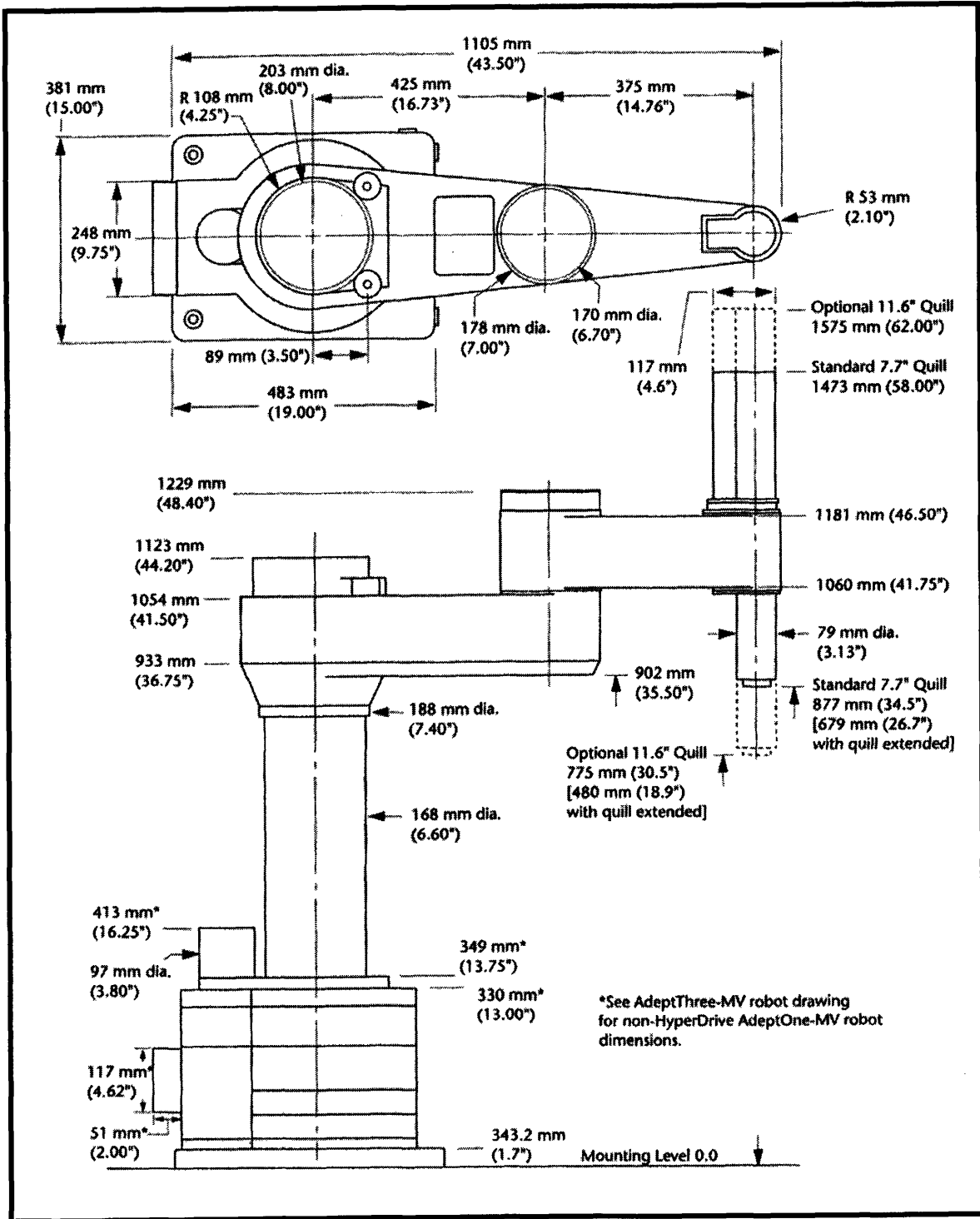


Figure A-1: Adept One Dimensions

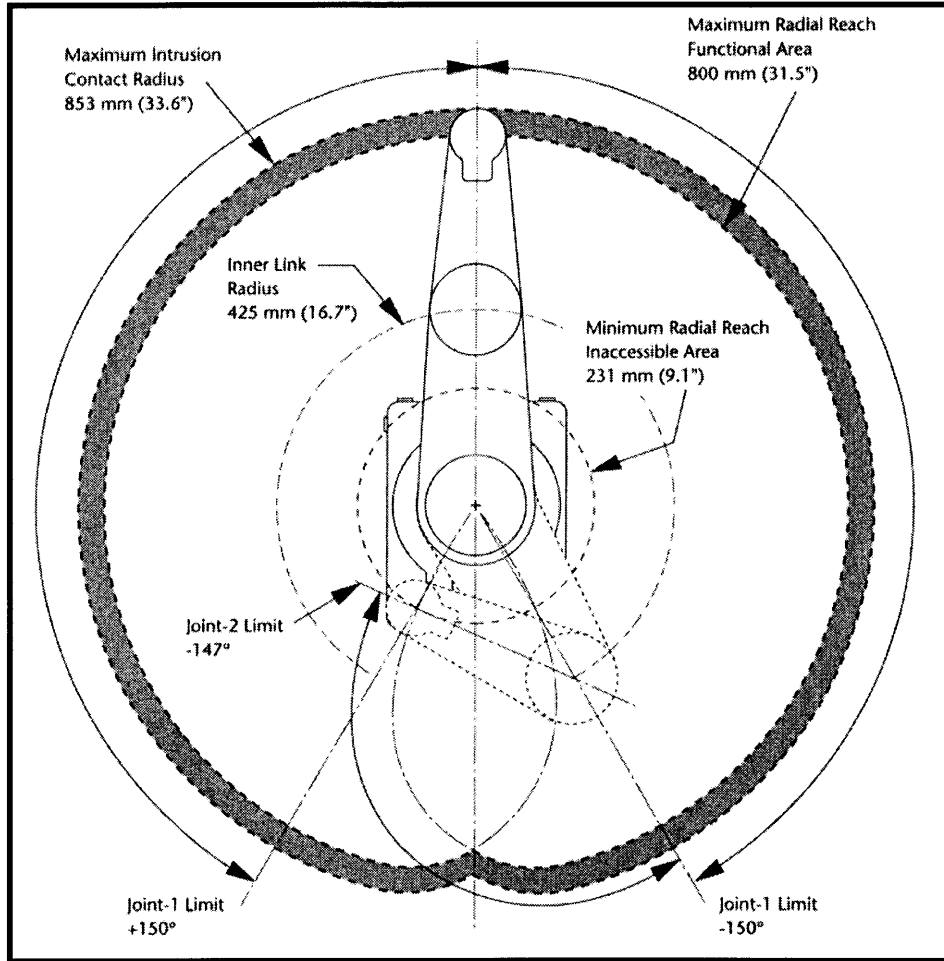


Figure A-2: Adept One Workspace

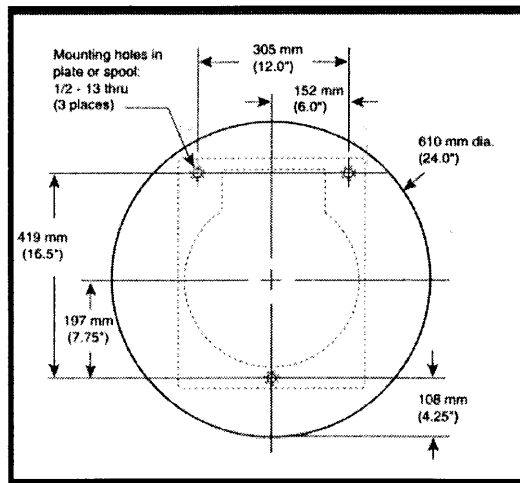


Figure A-3: Adept One Base Mounting Dimensions

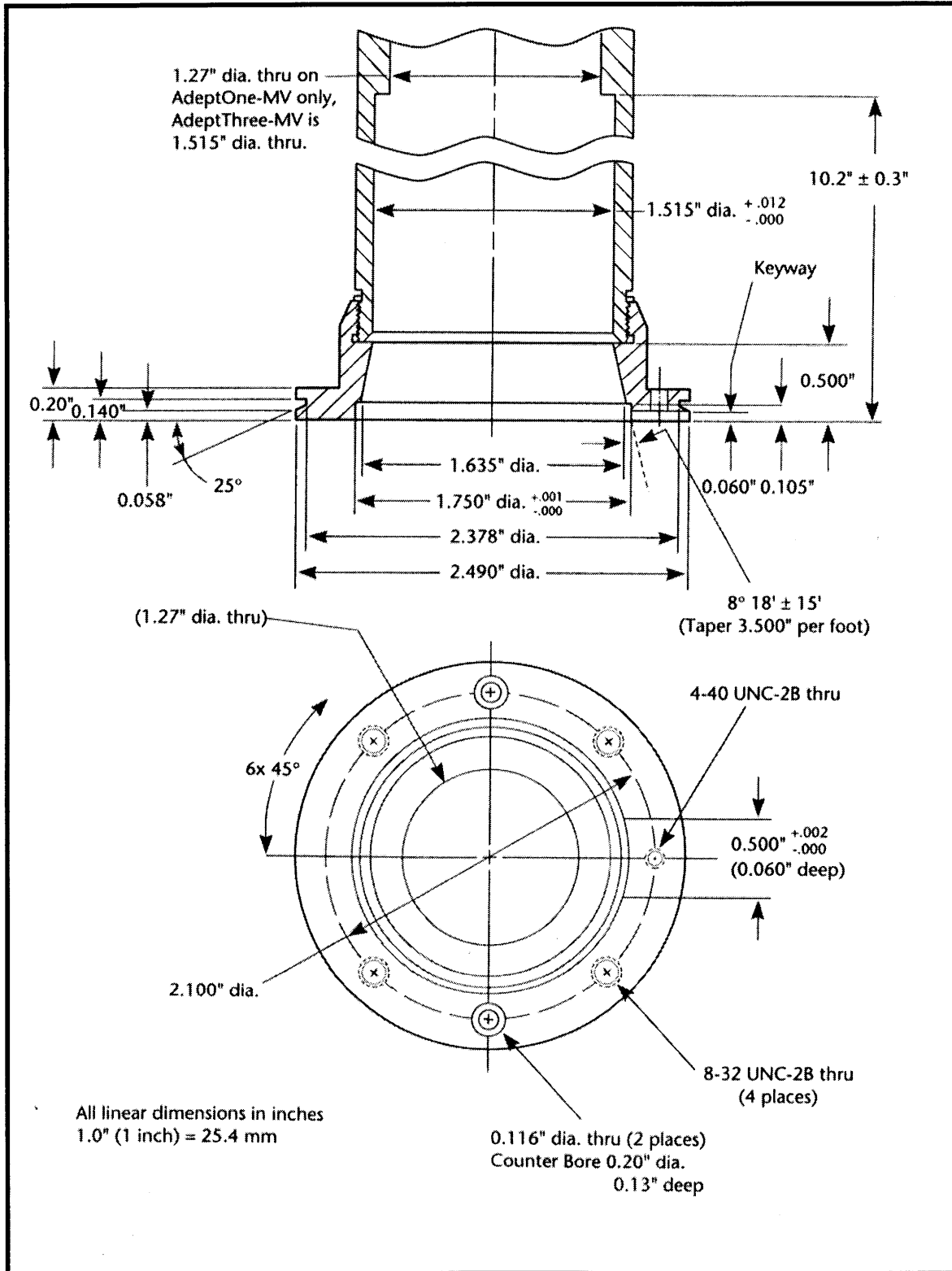


Figure A-4: Adept One User Flange Dimensions

Appendix B

Force Sensor Mechanical Specifications

A JR³ Universal Force-Moment Sensor System is being used as the wrist force/torque sensor in the laboratory RACS. The sensor is configured to fit the tool flange of an Adept One robot. The sensor is Model No. UFS-35A100-Adept. The sensor's load ratings are given in Table B-1.

Table B-1: JR³ Sensor Load Ratings.

Direction:	Rating:
Fx and Fy	100 lbs
Fz	200 lbs
Moments	350 in-lbs

The dimensions of the sensor are given in Figure B-1, (JR³, 1988).

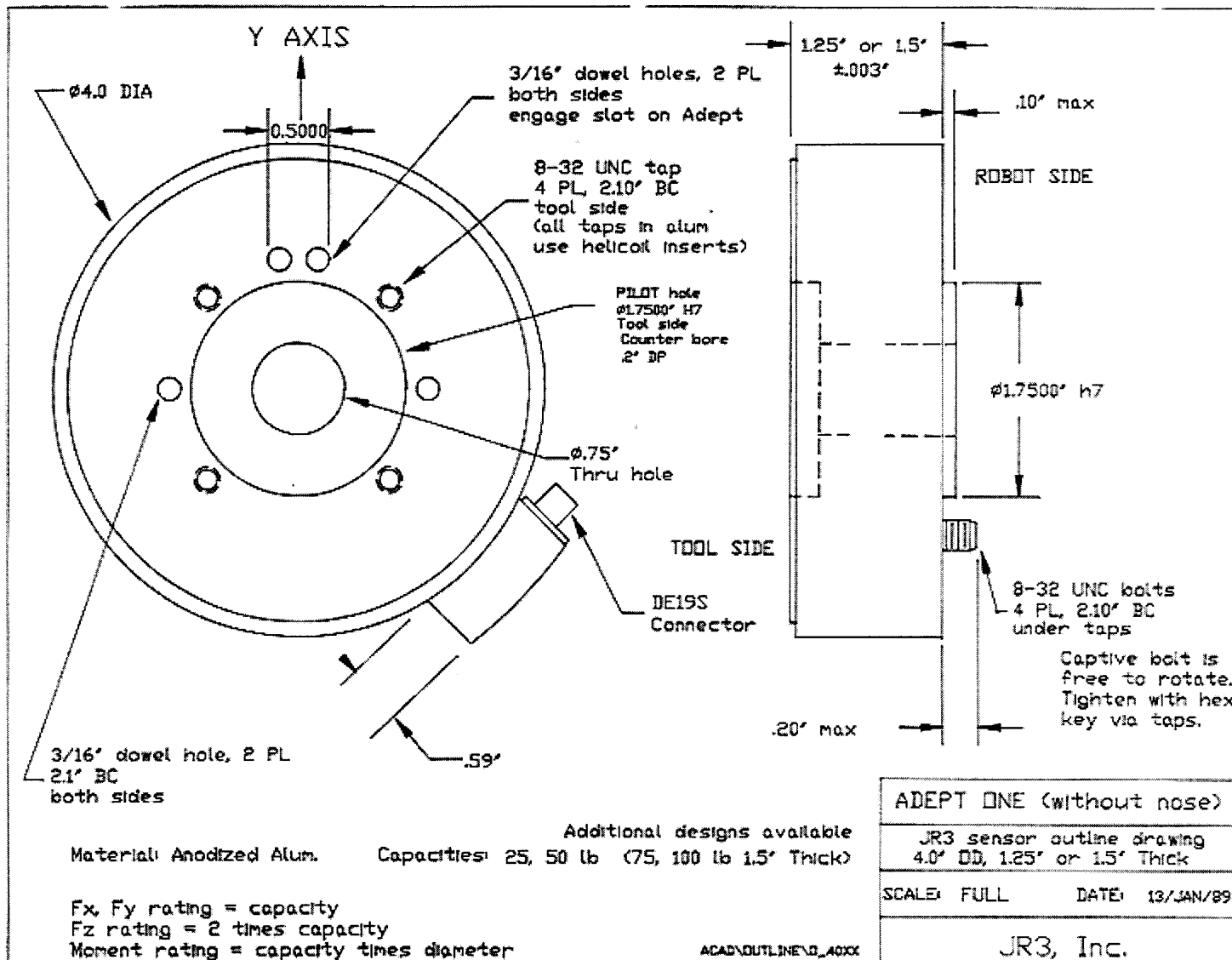


Figure B-1: JR³ Sensor Outline Drawing

Appendix C

Wrist Control Circuitry

Figure C-1 diagrams the circuit used to control the three wrist motors.

Each of the components are briefly described in Table C-1.

Table C-1: Control Circuitry Component Descriptions

Name	Description	Vendor
2224R and 1624	DC motors and magnetic encoders	Micro Mo
LMD18245	DMOS full bridge motor drivers	National Semiconductor
HCTL2016	16 bit, 4x Quadrature decoders	Newark Electronics
74ALS253	TTL 253 Data Selector/Multiplexor	Digikey
CTX101	1 MHz clock	Digikey
74ALS161B	TTL 161 Binary Counter	Digikey
PDIO-74	72 bit programmable digital I/O board	Analogic
V _{cc} = 40-45 V	Power supply for motor driver chips	

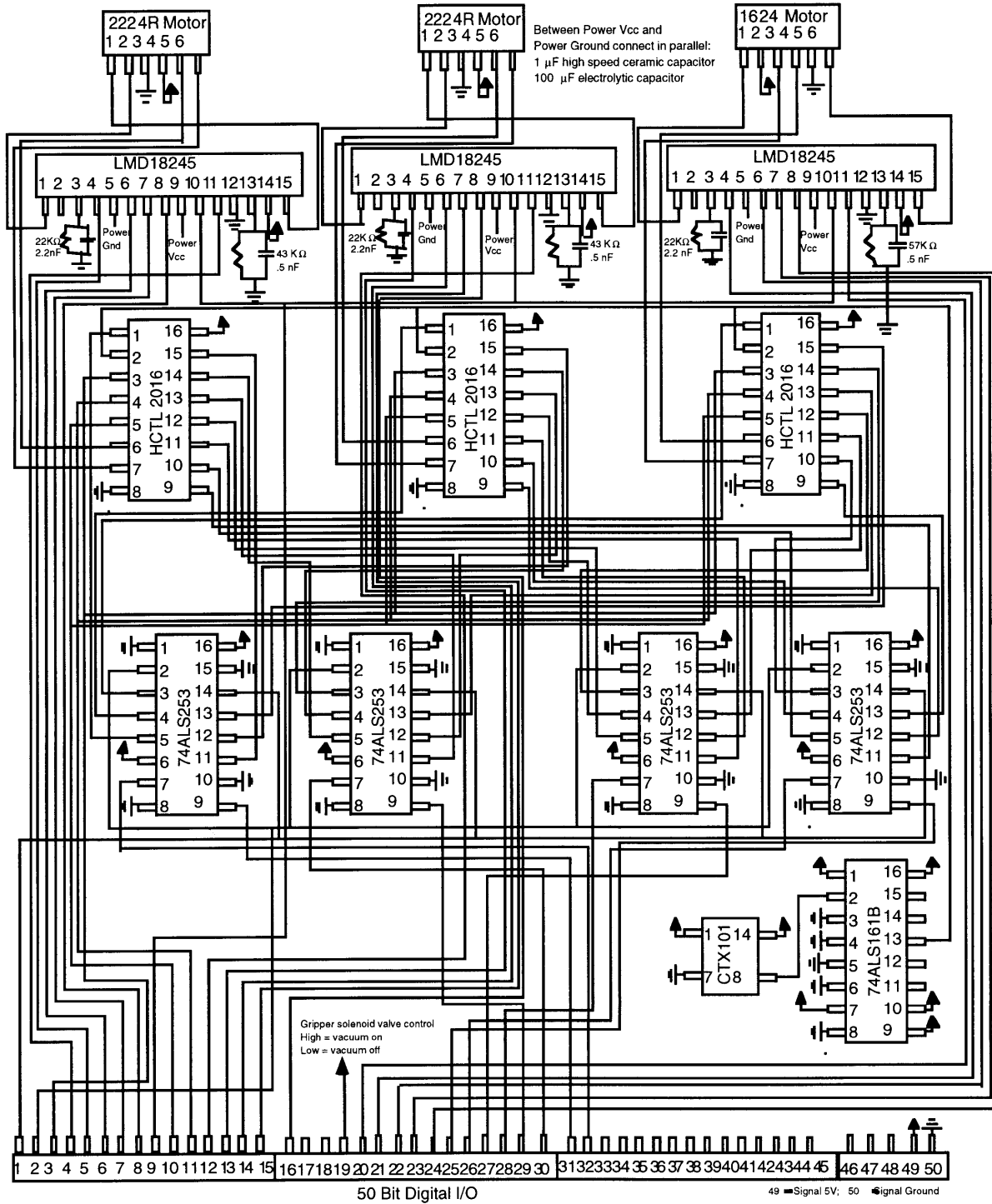


Figure C-1: Wrist Control Circuit Diagram

Appendix D

Test Nugget Characteristics

Twenty nuggets were selected from the 70 kg of polysilicon furnished to MIT by SEH. The nuggets were chosen based upon the anticipated difficulty that the nuggets would present to grasping. These difficult to grasp nuggets were used to determine the vacuum cup size and style best suited for a gripper. The same nuggets were also used to tune the manifold resistances of the designed gripper. The characteristics of these nuggets are summarized in Table D-1.

The features that can make a nugget difficult to grasp include: high weight, peaked or edged top surfaces, jagged and rough surfaces, highly sloped sides with respect to the horizontal, and a characteristic mottled surface that has a texture similar to cauliflower. The cross sectional of a nugget influences how many vacuum cups could easily grasp the nugget. However, other than having a surface area range of 20-40 cm², no definite relationship between nugget cross sectional area and mass was evident (Figure D-1).

Table D-1: Characteristics of Test Nuggets

Nugget	Weight (g)	Cross sectional area (cm ²)	Notable surface features	Grasping difficulty
1	204	39.5	Pointed top and highly sloped	Medium
2	158	48.0	Peaked, moderately sloped	Medium
3	264	40.3	Jagged, lightly sloped	Medium
4	160	40.7	Sharp peaks, rough, high slopes	High
5	192	43.5	1/2 highly sloped, 1/2 mild slope	Medium to high
6	216	46.0	Angular and smooth	Low to medium
7	76	35.5	Curved and highly sloped	Low
8	236	44.0	Rough peak and highly sloped	High
9	88	25.0	Very jagged, small	Medium
10	180	39.9	1/2 lightly mottled, 1/2 moderate slope	Medium
11	548	50.8	Largest nugget in sample, otherwise unremarkable	Medium
12	120	46.8	Lightly mottled	Low
13	220	35.9	Heavily mottled and sloped	High
14	290	53.6	Large, curved, and moderately mottled	Low
15	102	40.3	1/2 lightly mottled, 1/2 slightly rough	Low
16	228	38.7	Moderately rough, flat	Low
17	86	23.0	Rough and pitted surface	High
18	78	29.0	Rough and jagged surface	Medium
19	74	28.6	Concave	Low
20	84	34.7	Flat and heavily mottled	High

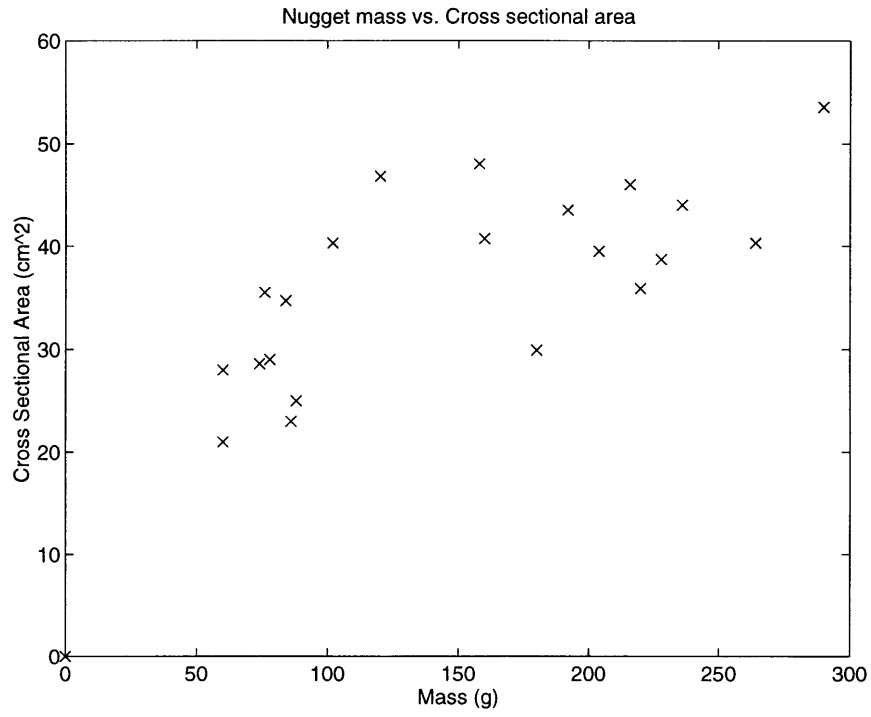


Figure D-1: Nugget Cross Sectional Area vs. Mass

Appendix E

Vacuum Pump Specifications

Specifications are from (Gast, 1992).



Post Office Box 97
 Benton Harbor, Michigan
 Ph: 616/926-6171
 Fax: 616/925-8266

Product Specifications

PART NUMBER: STD210
 REVISION: D

Model Number	Motor Voltage	RPM		HP	kW	Net Wt.		'A' DIM.	'B' DIM.
		60 cycle	50 cycle			lbs.	kg		
0523-4010-G562DX	100-115 100-110	1725	1425	.25	0.18	32	14.5	394 1322	11 1/4

SOUND LEVEL LESS THAN 70 dba
 NORMAL AMBIENT 1°C. - 40°C.
 RELATIVE HUMIDITY 8% - 100% NON CONDENSING
 ENVIRONMENT CLEAN DUST FREE

• TECHNICAL DATA SUBJECT TO CHANGE WITHOUT NOTICE.

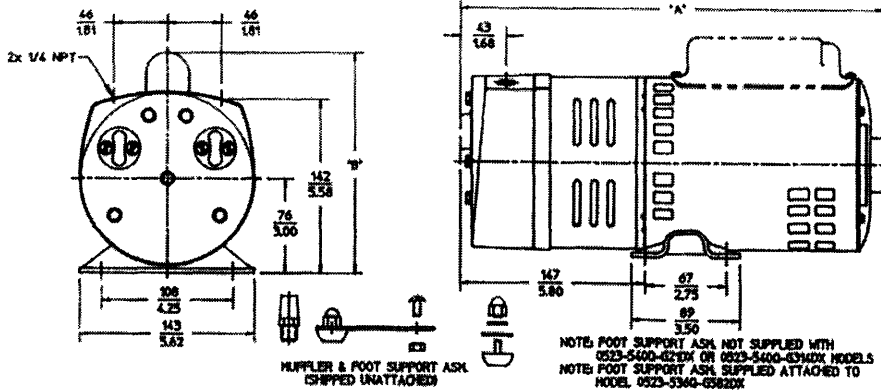
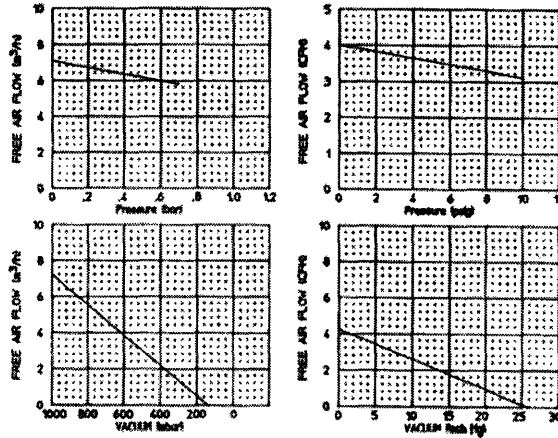


Figure E-1: Vacuum Pump Specifications