Total automation of an industrial in–line quality measurement system

Author: Colman Shouldice

Master of Engineering

Waterford Institute of Technology

Supervisor: David Walsh

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Declaration

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Presented to: Mr. David Walsh

Department of Engineering Technology

Waterford Institute of Technology

This Thesis is presented in fulfillment of the requirements for the degree of Masters of Engineering. It is entirely of my own work and has not been submitted to any other college or higher institution, or for any other academic award in this College. Where use has been made of the work of other people it has been fully acknowledged and fully referenced.

Signed: _______________

Colman Shouldice

Date: ______________

Abstract

This thesis summarises the design, development and installation of an automatic industrial in-line quality measuring and control system. The research project was initiated by a company manufacturing metallic balls for ball bearing assembly. The diameter tolerance of the components produced determines the value of the product and the market in which the company trades. Currently this company supplies the medium value market (automotive) and is striving to break into the higher value market (white goods). To do this, two aspects of the production system need be enhanced:

1. The frequency at which the product is sampled and
2. The level of precision measurement carried out during production.

The project caters to both issues with the development of a closed-loop automated measurement system with machine control feedback. The overall objective of this project is to develop a prototype for a two-machine sampling operation and conduct tests and experiments to access the justification for company investment in an automatic sampling and measurement system.

The thesis details the design and development of a component retrieval and transfer system, a component management system to normalize ball temperatures and feed the measurement device, an SPC based machine control system and the associated communication network. The design and proving of concepts, in a laboratory, is outlined. The building of the prototype, at the manufacturing plant, is described in detail; as is the rigorous testing and development of the prototype.

Finally, the outcomes from this phase of the project are discussed and assessed and recommendations are made regarding the future development of the system.

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1 Introduction

NN Euroball Kilkenny, Ireland is one of the leading suppliers of steel balls for ball bearing assembly in the car manufacturing industry. At present the company produces an average of 25 tonnes of steel ball per day from their factory in Kilkenny. It is through increased competition from other competitors with lower labour costs than that of NN Euroball Kilkenny, which has prompted the idea to automate their ball measurement process. There is potential for two main advantages with an automated measuring system:

1. An automated measuring system has the potential to increase the tolerance of the finished product using the same staff and machinery due to its capability of more frequent sampling and precise measurement. By increasing the tolerance of the finished product, the quality is increased. This generates less noise when the ball bearing is in use; this trait is desirable in the higher valve white good market. Here, the potential for more profit exists.
2. An automated sampling and measurement system has also the potential to decrease the cycle time (by up to 3 hours) of the grinding process as a higher level of control is possible. If the grinding process time is decreased, an increase in product throughput may be possible.

The main goal of the project is to develop an automated sampling and measurement test-rig for two production machines. The control panel of the two machines will be re-constructed to allow for a higher level controller to command their operation. The system will sample and measure from these two machine on a periodic basis. An automatic control chart for the product will be generated and used as a process guide to indicate the best working parameters of the machines and optimise control. This system will operate on a trial basis to indicate the potential of the system on a larger scale.

Present Method of Measurement utilised by the grind technicians*:*

Currently, the samples to be measured are manually picked at random from the grinding machine turn table by the grind technician and delivered to the measurement area. The samples are measured every hour. Standard balls of known diameter are used to calibrate the measuring system before the samples are measured. The results are then plotted on a cut-down chart for each particular ball size. The cut-down chart for a 13.494mm batch is shown in Figure 1.1.This method is time consuming and uses valuable human resources to complete a relatively simple and repetitive task. The objective of this proposed project is to automate this entire measurement procedure, and while the initial cost of research and installation may be significant, the potential and increase product value without a comparative increase in cost exists.

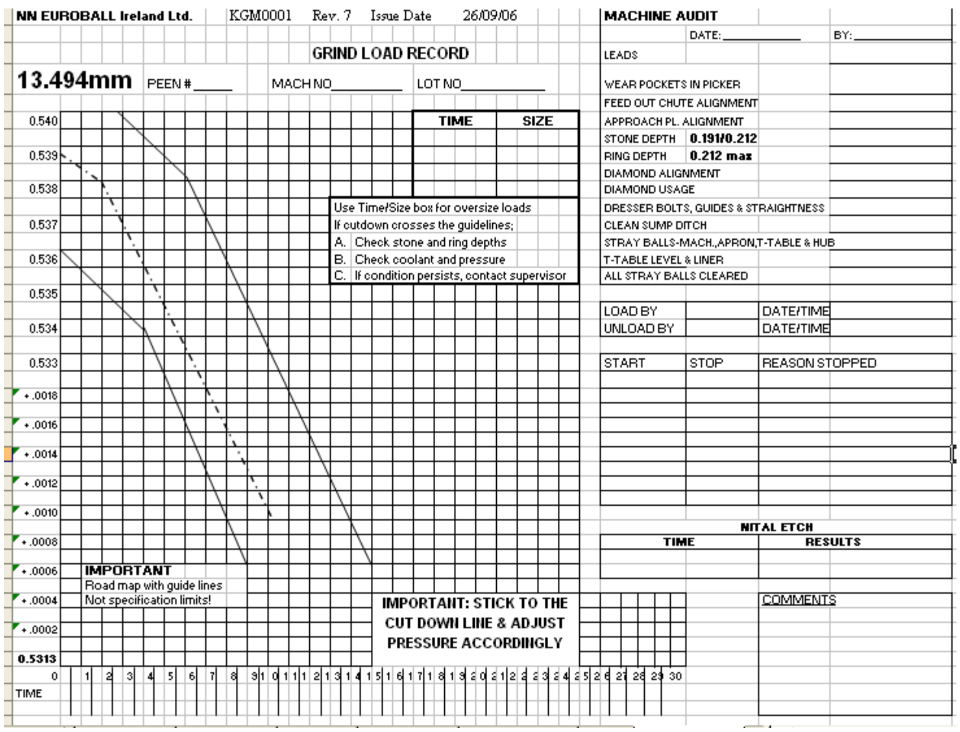


Figure 1-1 Cut-down chart of a 13.494mm batch for the grind process

This basic operation sequence of the proposed automated sampling and measurement system is as follows:

- Retrieval of a sample from the grinding machine turn table.
- Transportation of the sample to a temperature normalizing tank for temperature equalization with the reference/calibration component. (As this method of

measurement in one of comparative means, thermal expansion differences between the sample and reference must be excluded.)

- The sample is held at a fixed temperature for a pre-determined length of time.
- Feeding of the sample into the measurement device with two calibration components through a purpose made feeding unit.
- Calibration of the measuring unit using the standard components.
- Return of the calibration component to the temperature normalizing tank.
- Measurement of the bearing diameter using the custom built measurement unit associated with the project. The level of accurate measurement the instrument delivers is 1μm. (The instrument will hopefully deliver an accuracy of 0.1μm as the project progresses).
- Release of sample from the measuring station.
- This measurement is then graphed using statistical process control software to determine where the balls' diameter lies in relation to the control limits of the process.
- The central controller then controls the overall process by outputting a signal to the grinding machine controllers to increase or decrease the grinding stone pressure as required.

The block diagram in Figure 1.2 illustrates how these individual processes will link together in the proposed automatic sampling and measurement project.

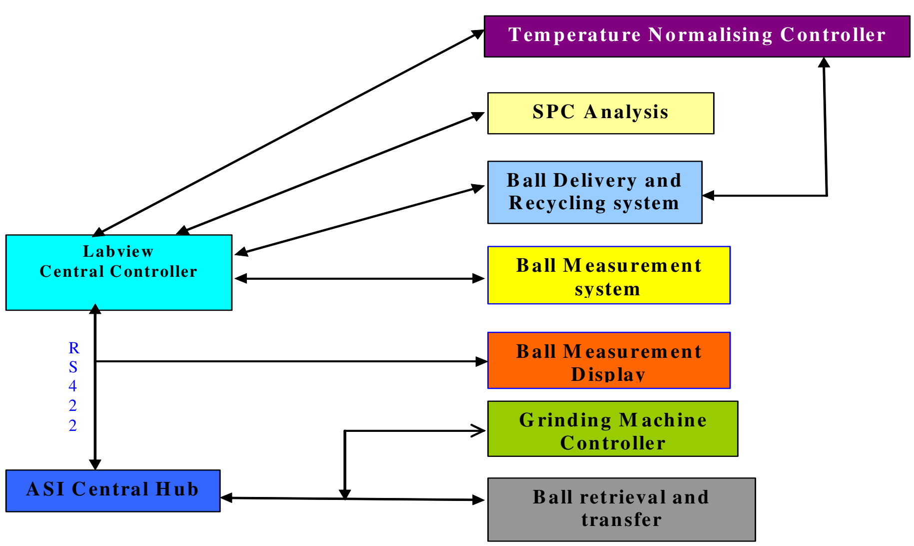


Figure 1-2 Communication links to and from the Central Controller

Advantages of the Proposed automated sampling and measurement System are as follows:

- Working with a measuring instrument capable of measurement in the sub-micron range which increases the likelihood of a superior finished product.
- A more elaborate component temperature equalisation process will allow for all ball measurements to be accurate and trustworthy.
- Ability to sample more often for precise process control.
- Potential increase in product value due to the installation of an automated sampling and measurement system.

The automated sampling and measuring system in planned to be initially installed in the grinding section of the production cycle. The cell contains 24 grinding machines, each of which are planned to be utilised in the automatic system (see Figure 1.3).

Figure 1-3 Grinding machines in the Production Plant

Before installation occurs the appropriate research must be carried out to access the viability of significant investment for the company in question (viability discussed in Conclusions Chapter). This research consists of, building a test rig for system simulation, conducting tests and gathering data. The results acquired may then be accessed by the company to aid their decision to develop the system. The research is divided into two sections.

1. The measuring instrument (presented in Chapter 4).
2. The automated sampling system with machine control feedback (the research on which this Masters of Engineering thesis is based)

1.1 Background

This section of the chapter discusses the automation and functionally on the proposed automatic sampling and measuring system. The Ball manufacturing industry and current standard is also discussed, along with a description of the duties and quality control checks carried out by the technicians throughout the grinding process.

1.1.1 Automation of the Quality Measurement System

The proposed sampling and measuring system will be controlled by a central controller. This central controller will be linked to the machine controllers via a network which will allow communication to and from the central controller. The proposed automatic system should operate as follows:

The central controller checks which machines are in operation and then requests every machine in operation to sample. The retrieval system selects a single ball at random from the grinding machine turn table and delivers it to a ball propulsion system. The retrieval system then repeats this function four more times. The five ball sample is then propelled to a central temperature normalising location where they are stored in one cooling pipe specific to each machine, which is submerged in a coolant. On arrival, a signal is sent to the central controller which starts the cooling timer. After the predetermined cooling time has elapsed, the controller signals the release of the sample set along with the corresponding upper and lower calibration balls. Seven balls are thereby lined in sequence in a ball injecting system. When the measurement device is ready, the delivery system injects the balls in sequence onto the measuring platform; the first two balls are the standard balls which are measured to calibrate the measurement device. These are then recycled through the system and sorted with the aid of a custom made ball sorting system, into their cooling pipes in the temperature normalizing tank. The sampled balls are then measured in turn and ejected from the system. The sample ball measurements are then saved to file. The average of the five sample ball measurements is then plotted on an automatic cut-down road mapping chart, which has been developed based on stock removal trials carried out during the course of the project. If the average measurement is above or below the control limits on the cut-down chart, the working pressure of the grinding machine will be automatically altered, to bring the next sample measurement within the control limits to optimise the process control.

The complete project can be broken down into ten different sections:

1. Ball retrieval,
2. Ball propulsion,
3. Ball Temperature Normalising,
4. Ball Delivery System,
5. Component Measurement,
6. Standard Component Recycling,
7. Measurement Analysis (SPC),
8. Machine Parameter Control,
9. Network,
10. Measurement Display.

The 5th and 7th section of the project listed above is part of the measuring instrument research and is presented in outline only, in this thesis.

The proposed sampling and measuring system must also cater for the range of sizes produced (10mm to 13.5mm): therefore, a generic ball handling and measuring system must be developed. Measurement is carried by comparing the sample to reference balls; therefore, within the system each sample must have an upper and lower calibration ball.

1.2 Measurement and the ball manufacturing process

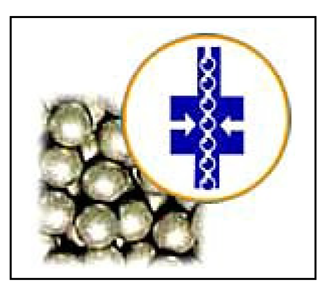
This section of the chapter describes the bearing ball manufacturing process and details some background information on the work carried out during the grinding process including an array of quality checks.

1.2.1 The complete ball manufacturing process

Before the steel used for bearing ball production enters the production process it is annealed. Here the steel is heat treated at a high temperature and control cooled to primarily soften the metal and to simultaneously provide change in its microstructure to improve machineability and facilitation of the cold working process. The steel is then introduced to the 5 stages of production starting with cold forging, and finishing with lapping. Figure 1.4 displays a typical example of the appearance of the bearing ball after each stage of production.

Figure 1-4 The 5 production steps of bearing balls [1]

The 5 stages of production are describes as follows:



1. Cold Forging [1]

Calculated length of wire is sheared and cold forged in a close die to give it the spherical shape.

2. Flashing [1]

The second production step is the rolling between plates with concentric grooves in order to eliminate the heading witness marks and to increase the precision of the ball. In this operation, the spheres are ground between two concentric pressure plates to correct the spherical shape and remove the seam formed in the cold forging.

3. Heat Treatment [1]

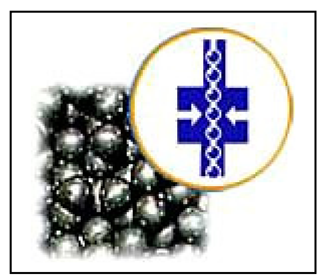
The balls are heat treated i.e. Hardened and tempered to attain the desired level of hardness and microstructure. The heat treatment, when necessary, gives the maximum possible hardness and the desired microstructure to the ball and therefore the best obtainable technical features in compliance with materials used.

4. Grinding [1]

Here the hardened balls are ground to improve surface finish and geometrical parameters. Several careful grinding processes with ceramic wheels lead to a higher size precision preparing the balls for the next final lapping operation.

5. Lapping [1]

The final lapping operation gives the ball a perfect bright, compact surface, without any defect, with a very low surface roughness, very low deviations from spherical form, very low waviness values and total lack of surface defects assured by optical control machines.



Before packaging and dispatch, the product undergoes inspection where each and every parameter of the balls is thoroughly inspected. All precision, hardness, material features, etc. are tested at every stage of the production and again at the end of the manufacturing process before shipping, in order to assure and guarantee the product quality.

1.2.2 Description of the entire grinding process and QC [2]

The following is a description from the company standard operating procedures, of the step by step process instructions including quality control checks carried out by grind technicians. This is given as a typical example of the control currently used in production.

1. **Leads**

- Check lead length, depth, and width using the machine audit section of the grind load record (see Figure 1.5).

MACHINE AUDIT		
	DATE: ______________	BY: ________________
LEADS		
WEAR POCKETS IN PICKER		
FEED OUT CHUTE ALIGNMENT		
APPROACH PL. ALIGNMENT		
STONE DEPTH	**0.191/0.212**	
RING DEPTH	**0.212 max**	
DIAMOND ALIGNMENT		
DIAMOND USAGE		
DRESSER BOLTS, GUIDES & STRAIGHTNESS		
CLEAN SUMP DITCH		
STRAY BALLS-MACH.,APRON,T-TABLE & HUB		
T-TABLE LEVEL & LINER		
ALL STRAY BALLS CLEARED		

Figure 1-5 machine audit details

2. **Picker/Take-Off Chute**

- Inspect the picker for wear pockets.
- Inspect the picker to ensure that scalloped edges are inside the grooves enough to prevent balls from bypassing the picker.
- Inspect the take-off chute for stray balls.
- Inspect the take-off chute to ensure that it is secure. This is especially important on bigger ball machines.

3. **Approach Plate**

- Inspect the approach plate alignment with leads of stone.
- Inspect the approach plate leads in relation to the leads on the ring.

4. **Stone**

- Check the stone depth and groove-to-groove variation.
- Inspect the stone for cracks and chips.

5. Rings

- Check the ring depth and groove-to-groove variation.
- Inspect the ring grooves to ensure the balls are in contact with the entire groove.

6. Diamond Dresser Assembly

- Diamond dresser inspection; compare the readings found with minimum groove depth and maximum groove depth on the stone depth chart as shown in Table 1.2. If actual groove depth is within the minimum and maximum, check the wheel flatness with a straight edge.
- Check the general condition of the diamonds, holder, and wear bars.
- If all of the above inspections show the wheel condition to be proper, then proceed with other set-up checks.
- If grooves are deeper than the maximum, then the wheel must be redressed to the average.
- Close the machine, reset diamonds, and begin the dress cycle. Always run with coolant on and use manual pressure. Stop occasionally and recheck the groove depth; repeat until average depth is reached.
- Reset the dresser to make face contact with the stone.

BALL SIZE			RING			STONE		DIA SETTING NEW RING
FRACT	DEC	METRIC	NEW (22%)	PULL 36%-40%	FACE (10%)	MIN 34%-36%	MAX 40%	
	0.393701	10	0.087	0.149	0.039	0.141	0.157	0.165
13/32	0.406250	10.319	0.089	0.154	0.041	0.146	0.162	0.171
	0.413380	10.5	0.091	0.157	0.042	0.149	0.165	0.174
	0.433071	11	0.095	0.164	0.043	0.155	0.173	0.183
7/16	0.437500	11.113	0.096	0.170	0.044	0.157	0.175	0.184
	0.450	11.430	0.099	0.175	0.045	0.162	0.180	0.189
	0.452755	11.5	0.100	0.176	0.046	0.163	0.181	0.190
15/32	0.468750	11.906	0.103	0.182	0.047	0.168	0.187	0.203
	0.472441	12	0.104	0.184	0.047	0.170	0.188	0.198
31/64	0.484375	12.303	0.107	0.193	0.048	0.174	0.193	0.203
	0.492126	12.5	0.108	0.197	0.049	0.177	0.197	0.207
½	0.500000	12.700	0.110	0.200	0.050	0.180	0.200	0.210
	0.511811	13	0.113	0.204	0.051	0.185	0.204	0.214
17/32	0.531250	13.494	0.117	0.212	0.053	0.191	0.212	0.223

Table 1-1 groove depths

7. Loading

- Using hoist, lift a hopper onto knife – edge trolley.
- Check using a micrometer two balls and put under knife edge.
- Close ring and stone to ensure that no balls can fall between them. Do not allow stone to touch diamonds.
- Using knife edged trolley or pre bar-grated load, load a lot into the turntable.

8. Start-Up

- With pressure on manual, open up ring and stone until balls fall into grooves.
- Jog stone on manual pressure to where the balls barely pull through the ring and stone.
- Again, with pressure on manual, start machine at approx. 50 PSI above the pressure required to move the rotating ring. Continue to increase the pressure until all grooves feed.
- Adjust the pressure to approximately 500p.s.i. (34.5 bar) over the pressure required to move the rotator, and allow to cycle until variation is gone.
- The amount of pressure that is been applied to the production balls between the ring and the stone is set by controlling the amount of current that the main motor can pull. The greater the pressure on the ball, the greater the current used by the motor and vice-versa.
- Set ammeter min and max to hold amps at between 40 and 45. Switch pressure to automatic and cycle. On big ball sizes, the pressure may be left on manual, if the feed is erratic.
- Ensure the feed-board to the approach plate is completely full of balls and that all grooves are feeding at the correct angle. Ensure also that no separation of the balls is occurring within the approach plate. Coolant should not be used to force feed the balls to the stone.

9. Running

- Record and plot results on the cut-down sheet (see Figure 1.1). Follow “Road Map Line”. If cut rate goes outside the control limits, it can be caused by the following: Too much pressure, Stone groove's too deep or insufficient coolant. Adjust accordingly with extra gauge checks to verify. If cut rate is too shallow, it can be caused by the following: insufficient pressure, stone groove's too shallow or ring groove's too deep. Adjust and verify as above. Ensure all grooves are feeding correctly

- Ensure adequate coolant flow
- While running normal product at +.0004" above dump size put machine on round-up cycle reducing PSI to 800.

Load Completion - Qualification for Lapping

- Balls must be dumped to within ±.0001 of specified dump size.
- Measure three sample balls for size variation.
- Complete all move tags, load records, and control charts.
- The addition of the operator's initials to the Move Tag indicates he/she has checked and verified that the quality meets the specified requirements.

10. Process Control Grind

- At completion of load, the Operator must fill out the following: Date, Lot Number; Ball Size, Cycle time and Operators initials.

11. Unloading

- Shut the grinder down and switch the hydraulic pressure to manual.
- Depress the "pressure release" and "out" buttons simultaneously until the balls at the top of the ring exit the take-off chute.
- Verify that the diamonds are not in contact with the stone. This will prevent stone damage while running the turntable to unload balls.
- All balls are then jogged out of the machine, with no pressure on gauge.
- Inspect the turntable and hub for stray balls.

1.3 Project Objectives

The objectives were established before any work began and are outlined as follows:

Development of a test rig (Pilot Plant) (The term "Pilot Plant" refers to the temperature normalizing and measurement system. Although it is not a Pilot Plant, it is referred to as one (in nick name only) by the people involved in the project). This Pilot Plant should consist of a measuring container and a temperature normalizing container where the samples temperature is equalized to that of the reference/standard components. The system must have a means of organising the samples and standard balls before releasing them to the measuring container for measurement, and a method of re-circulating the standard ball to the temperature normalizing tank after each measurement. The coolant temperature difference within the Pilot Plant must be controlled to a level less than that which would cause measuring instrument offset due to thermal expansion difference between the sample and standard ball.

Development of a transfer system; firstly to retrieve the sample from the grinding machine turn table and secondly to deliver the sample to the Pilot Plant which is centrally located within the production plant.

Control modification of two machines. Currently the machines are hardwired and their control is maintained through the use manual contact witches. This control system must be modified to allow for a more automatic and flexible means of control with a means of communication with the central controller.

Development of a system network with SPC control is required to allow communication between the central controller and the automatic machine controllers on the Plant floor. When the sample measurements are taken the SPC control system will plot the result on a cut down chart, and depending on its location a change in the machine working pressure may be signalled to the machine controller.

Further Objective: During the project the addition of another objective was introduced. The development of a measurement display unit was required and situated at the associated machines to aid the transfer from a manual to an automatic system.

2 Technical Review

Before project design and prototyping commenced, each aspect of the project was researched to gain knowledge of the existing technology utilised in industry and an insight into the most logical and effectives strategies to enhance the project's level of success. This chapter discusses the technical aspects of the project and outlines, where possible, the alternatives to the strategies undertaken and equipment used. Contrasts are made between the selected plant elements and their alternative, and the reasons for the final selections are detailed. A brief background on the history of ball bearing and the materials selected for bearing ball production is also outlined.

2.1 Ball Bearing Background

A bearing is the support and guide for a rotating, oscillating, or sliding shaft, pivot, or wheel [3]. It is a device which permits constrained relative motion between two parts, typically rotation or linear movement. Bearings may be classified according to the motions they allow and according to their principle of operation as well as by the directions of applied loads they can handle. Ever since objects have been moved, round rollers were used to make the job easier. Eventually developed was the idea of securing the roller to whatever was being moved, creating the first vehicle with wheels. However, these used bearings known as plain bearings made from materials rubbing on each other instead of rolling on each other. A typical plain bearing is made of two parts; a rotary plain bearing can be just a shaft running through a hole. It wasn't until the late eighteenth century that the basic design for bearings was developed [4]. Development continued through the nineteenth and early twentieth centuries, spurred by the advancement of the bicycle and the automobile.

The purpose of a bearing is to reduce friction and support radial loads (Load applied perpendicular to the bearing axis of rotation) and axial loads (thrust load, applied to the bearing parallel with the bearing axis of rotation); bearings reduce friction by providing smooth metal balls or rollers, and a smooth inner and outer metal surface for the balls to roll against. These balls or rollers "bear" the load, allowing the device to spin smoothly. Generally one of the races is fixed; this allows the second race to rotate which also causes the balls to rotate. As one of the bearing races rotates it causes the balls to rotate as well. This rotation causes a lower coefficient of friction, than if the two flat surfaces were rotating on each other.

2.1.1 Bearing Ball Materials

Bearing steels must posses high strengths, toughness, wear resistance, dimensional stability, manufacturing reliability, mechanical and rolling contact fatigue resistance and freedom from internal defects [5]. There are essentially two choices for the material used in balls for bearings, stainless steel or chrome steel.

In corrosive environments, stainless steel balls are preferred where corrosion and chemical resistance are required. These materials have evolved in response to different manufacturing and application needs; they are also commonly specified for food and beverage processing machinery, medical applications, medicine equipment and aerospace applications [6]. Three of the most common types of stainless steel used are DR Stainless steel, AISI 440C Stainless steel and ES1 Stainless steel. DR Stainless steel is used in the manufacture of most corrosion resistant balls. DR Stainless steel has been specially developed to give excellent lifetime and low noise characteristics, combined with superior corrosion-resistance.

Another common type of stainless steel used in ball manufacturing is AISI 440C Stainless steel. This material has a very high carbon content is responsible for exhibiting excellent toughness and hardness properties; following heat treatment type 440C attains the highest hardness of any stainless steel, while maintaining a good resistance to corrosion. This material is used extensively for bearing ball applications where precise tolerances and surfaces are required [6].

ES1 Stainless steel is a relatively new stainless steel. This formulation has excellent machineability [6], with a corrosion resistance at least equal to AISI 440C .

The balls to be measured in this project using the automatic in-line, high resolution piezo measurement instrument are made of chromium steel hot rolled spheroidized wire rod as well as small diameter cold drown spheroidized rod. This material is supplied in coils by mills in the spheroidized-annealed condition; this is a heating process to create globular carbides in the rod [6]. The specific chromium steel used is SAE-AISI 52100: this is the standard material used for ball bearing applications where load capacity is the consideration. This steel is relatively inexpensive and is the most widely used steel for the manufacture bearing balls; its hardness, at about 62 HRC (Hardness on the Rockwell "C" scale) leads to good wear resistance and rolling contact resistance. The machineability of this steel is excellent; giving smooth, low noise ball finishes, together with superior life. In corrosive environments however it is not recommended to use chrome steel balls. This is a relatively inexpensive material.

SAE-AISI 52100		
Element	**Minimum Percent**	**Maximum Percent**
Carbon C	0.98	1.05
Manganese Mn	0.25	0.45
Phosphorus P	-	0.02
Sulphur S	-	0.008
Silicon Si	0.15	0.35
Chromium Cr	1.35	1.6
Copper Cu	-	0.2
Nickel Ni	-	0.25
Molybdenum Mo	-	0.08
Oxygen O	-	9.0 ppm max
Titanium Ti	-	30.0 ppm max
Aluminium Al	0.01	0.05

Table 2-1 SAE-AISI 52100 Chromium Steel Chemical Composition [6]

This steel is a high-carbon chromium alloy steel (see Table2.1). The hardness of steel is increased by the addition of more carbon. Adding carbon up to about 1.5% can increase the wear resistance of the steel, beyond this point the increase of carbon reduces toughness and increases brittleness.

The addition of chromium in the steel increases the hardness penetration and also increases the toughness and wear resistance. The amount of chromium in the AISI 52100 steel is what distinguishes it from the stainless steels previously discussed (steels with 12% or more chromium are referred to as stainless steels). The Manganese and Silicon in the steel when used with other alloys help increase the toughness and hardness penetration of the steel.

In the annealed condition this steel is comparatively easy to machine, however very high hardness and abrasion resistance can be developed by heat-treatment to make the steel particularly suitable for ball bearing applications where extreme wear resistance is required.

2.2 Component Handling

This section of the chapter details some existing pick and place system designs with similar properties to the unit fabricated for this project. Also outlined in this section is an alternative method to the ball propulsion and piping system.

2.2.1 Pick and Place System

Before the specific design for the custom made pick and place unit was considered, significant research was carried out to access some of the existing pick and place systems which are utilised in industry. The published information was limited but a variety of commercial pick and place systems were outlined on the internet. Some of the dimensions and functions of these existing pick and place designs were taken into account when designing the custom made pick and place unit outlined in this thesis.

Contrasting issues between conventional and required pick and place designs.

The commercial pick and place units outlined below, like all pick and place systems, are custom made to suit a particular application. The relevant features of the existing commercial systems are based on precision movement and placement with varying ranges of movement. The majority or industrial pick and place systems are controlled by electronic circuitry.

Compared to the precision and functionality of manufactured pick and place systems, the level of complexity required for the unit in the project is relatively low. The one major difference between the required unit design and the more conventional designs is that the component to be retrieved is in continuous motion in the turn table. Because of this, the unit design had to be custom designed. Another significant difference between the required unit design and the more conventional design is the level of robustness required. The pick and place unit must extend into a batch of moving steel balls. The common pick and place systems are designed to retrieve stationary components. The system design in this case therefore must be considerably stronger and harder wearing.

The means of operation in the more conventional designs is by electrical stepper motors. This method allows for a more precise operation with a high level pick and place location accuracy. For the design of the unit in this project the accuracy requirement is not so great, therefore, the picking device retrieves a sample at random from the batch of components. As the picking device does not need accurate location, a pneumatic cylinder can be used to extend and retract the pick and place unit. This would be a simple and highly durable design and was considered as the best method of actuation due to the mechanical impact in the retrieval process. The custom made pick and place unit design, fabrication, and installation in detailed in Chapter 3.

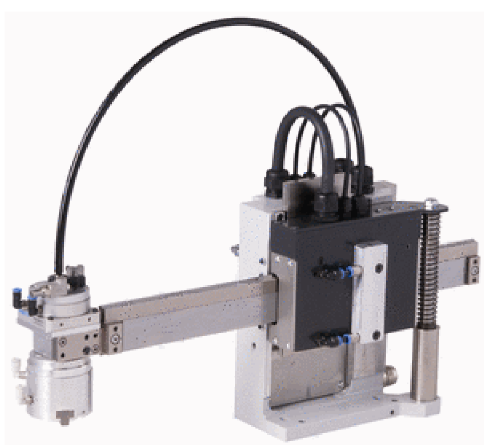
The applications of some of the custom-made pick and place units referred to previously, are outlined below. This information was taken from the website of each specific manufacturer, to give the reader an insight into the working features of existing system used in industry. End-effecters for different applications tend to be uniquely designed to suit the specific application, whereas the method of controlling the mechanical arm is likely to be a more generic system. This can be seen with the design of the pick and place system used in this project, where a number of alternatives could have been used to extend and retract the pick and place arm, but the options in relation to the end-effecter design is limited because of the component shape and movement.

The Yamaha YP-X Series [7]

The YP-X Series from Yamaha Robotics offers six models, including 2 axes and 4 axes types, for high speed pick and place operations. High speed pick and place operation at 0.45 sec. cycle time provides extremely high productivity (operating conditions of 50 mm in vertical direction, 150 mm in longitudinal direction, 50 in arch volume and 1 Kg load). Since it is possible to output a signal to turn any external equipment on or off from any position while the axis is moving, the actual production cycle time is further reduced. Because of Yamaha's unique servo system, settings for the stop point and operation pattern can be programmed freely. This makes the YP-X Series ideal for applications where there are multiple items in a small lot, an operation that is difficult for cam-type robots to perform. The design of the moving arm structure eliminates peripheral interference and saves space when operating on an assembly line.

Weiss HP Pick and Place Linear Motor Driven [8]

The Weiss HP pick and place handling module was designed by Precision Detroit Company. It is freely programmable in both horizontal and vertical axes; the device is directly driven by highly dynamic linear motors. The direct drive components permit fast mechanical movements.



Its' linear guidance system uses recirculation linear ball bearings which are quiet and more accurate than pneumatic units. Also included, is an integrated overload protection and an integrated lubrication system.

2.2.2 Sample Propulsion System

Upon commencing prototyping, the production plant layout was assessed to identify the most practical solution to transfer the samples. Because of the distance of sample transfer and location of machinery, both overhead and underground systems were considered. The underground system was excluded due to cost and difficulty of servicing such a system. The focus was therefore on an overhead conveying system. The propulsion options were narrowed down to two, both of which involved an enclosed piping system. The main decision was whether to push or pull the sample through the piping network. These options are assessed as follows:

Option #1:

This method centred on a vacuum system, extensively used in financial services, where a piping network carries containers of money to a secure safe room. This system transfers plastic containers of a standard fixed size being placed in a vertical post, and upon activation of a start signal a vacuum system is applied to the pipe to successfully lift the container upwards into an overhead piping network and to its final destination.

Advantages:

- Quick clean operation, no damage to balls, proven system.
- Uses a centralised vacuum system for all pipes and not one at each deposit site.

Disadvantages:

- Vacuum system very expensive (thousands of uro) to buy and run, only works with standard containers (not suitable for a range of different sizes)
- If centralised vacuum is inadequate or fails then the entire system would stop functioning.
- If the overhead piping network blocks, the complete system fails.
- This method is difficult to automatically synchronize with a loading system and release system at the transfer destination.

The operation of a commercial vacuum transfer system is outlined as follows:

Pneumatic Dispatch [11]

The following is a description of a vacuum system form a pneumatics company known as Eagle Pneumatics:

Airlift systems completely eliminate the need for messengers in most operations. Pneumatic Dispatch systems are compact and high-capacity, providing two-way carrier travel in a single tube. Installation is straightforward with no complicated power wiring. Airlift Pneumatic Systems can deliver anything that fits in an Eagle Carrier to any remote location. Small parts, orders, invoices, credit cards, shipping papers, memos, currency, mail, laboratory or test samples, medical supplies, or any other load weighing up to 5 lbs, are transferred at speeds up to 25 feet per second on a jet-stream of low-pressure air to a destination up to 2,000 feet away. Conveying tubing and bends are made from either strong, lightweight, non-corroding, dent-resistant PVC or optional steel. And Eagle's unitised Send/Receive Stations with built-in turbo blowers can sit on desks or tables, or mount easily in a minimum of space on walls, building columns, or any convenient flat surface, without using prime plant floor space.

A reliable pressure/vacuum system requiring power only at one end of the system in a Send/Receive station called the "Power Pedestal" that can be located at either end of the system. The Power Pedestal moves the carriers under pressure in one direction and under vacuum on the return in a "push-pull" system operation. This design allows the installation of intermediate Stations for greater system usage and flexibility.

Figure 2-1 Mark II Station and object carriers

User simply loads a Carrier and places it in the send/receive compartment. After closing the door, the push of a button dispatches the Carrier immediately to its destination, simultaneously locking the door of the receiving Station at the other end until the air flow stops just before the Carrier arrives. At the same time, red and white lights illuminate on the receiving Station to indicate that a Carrier is in transit. When the Carrier arrives at the receiving Station, the red signal light is extinguished to indicate the Carrier's arrival. The white signal light remains ON until the receiving Station door is opened.

DIMENSIONS

System Size	3"	4"	6"
A	9 1/8"	10 1/8"	12 1/8"
B	28 1/8"	34 1/8"	46 1/2"
C	4 3/4"	4 3/4"	4 3/4"
D	10 1/8"	11 1/8"	11 1/8"
E	4 1/2"	5"	6"
F	5 1/8"	5 1/2"	5 1/2"
G	1 7/8"	1 7/8"	1 7/8"
H	5/8"	5/8"	3/8"

Figure 2-2 pneumatic dispatch available piping dimensions [10]

Option #2:

This method would blow the samples with a large volume of air to effectively carry the balls through the pipe-work their destination. This system would require a means of loading the ball into the network and providing the air power required to transport it at each and every entry point.

Advantages:

- Fast operating time.
- Ability to adjust air pressure at each entry point. i.e. counteract the difference in size of ball bearing (smaller ball more air pressure)

- In the event of air pressure failing at one deposit point, then only that point is affected.
- Cheaper to implement incrementally than option #1.
- Simpler control if treated as separate systems i.e. (one pipe per machine).

Disadvantages:

- A propulsion system must be provided at each and every entry point.
- To be economical the propulsion system for each deposit point must be relatively inexpensive to install and maintain to justify option #2 being implemented.

Decision

Option #2 proved to be attractive for the project as it could be promptly tested as a prototype with limited expense. Option #2 also provided simpler local control which was attractive given the incremental nature of the project. As a failure of the piping network or vacuum system in option #1 would stop all other transportations through the entire system this was considered unacceptable. The predicted difficulty with synchronising option #1 with the retrieval system and delivery system was also a major deterrent.

2.2.3 Selected Piping Material

When selecting a piping material for the transfer network in this project a combination of five factors were assessed.

1. Durability.
2. Functionality.
3. Range of sizes available.
4. Ease of installation.
5. Expense.

Based on these factors, both Poly Vinyl Chloride (PVC) and steel piping were considered and the decision to PVC was made because the contrasting points in table 2.1.

Plastic PVC Conduit:	**Steel Conduit:**
• It's a very light weight and inexpensive product that is available in 3m lengths.	• Same as plastic conduit except it is stronger, more rigid and can withstand higher pressures due to the fact that all parts are threaded together.
• The problems of sharp bends and tight corners are solved using electrical conduit as it has many standard parts associated with it, including glands and adaptors for various sizes, 90 degree bends, tee pieces and clips for its installation.	• Steel is more likely to cause indentation on the steel ball as they impact on the 90 degree bends at high speeds.
• It is also flexible and can be bent without weakening or causing obstruction to its cross sectional area i.e. therefore not stopping a ball bearing travelling through a tight corner.	• Steel conduit can also suffer more from thermal expansion over long distances where varying temperatures occur and so careful design considerations must be followed to avoid damage i.e. buckling.
• The system also requires very little work to assemble also to the fact that unlike steel conduit it has push together fittings that can be glued for high-pressure applications. Unlike steel conduit it is also flexible enough to allow expansion over long distances without damage to the network. i.e. it can slide within itself.	• Steel conduit is much heavier with poor flexibility and hence creating difficult and expense for installation. Steel is also more susceptible to corrosion.

Table 2-2 Contrasts between PVC and Steel for transfer system piping

2.3 Pilot Plant Temperature Control

The following section outlines the research which inspired the methods of construction and control utilised in the Pilot Plant temperature control system. Also included are descriptions of the leading commercial oil baths which are mainly used for calibrating measuring equipment.

2.3.1 Temperature Control Review

The Pilot Plant construction and fluid temperature control is discussed in Chapter 4. The most relevant publications found in this topic area are associated with the developments of oil and water baths used for the calibration of temperature measuring instruments. The majority of these publications sourced were based on the uniform temperature control in the mK range. One relevant experiment was conducted at the Thermometric division of the Italian Institute of Metrology. A liquid oil bath was designed, manufactured and characterized with the aim to provide a suitable device for the calibration of thermometers at the mK level in the range from −10 °C to 100 °C. The temperature of the bath in the measuring zone is stable within a few tenths of a mille Kelvin in the whole range over a period of several days and it is independent from fluctuations of the ambient temperature. The bath shows vertical and axial temperature uniformity within a few tenths of a mille Kelvin over 10 cm in the central part of the measuring zone. [11]

Comparison calibrations were performed in liquid baths with silicone oil as the fluid medium in the range 90 °C to 200 °C by the Swedish National Testing and Research Institute. A calibration bath was constructed and presented at the 21st Nordic conference on Measurements and Calibration in 1999. The principle of the bath is based on a closed end aluminium tube, with an inner open concentric tube placed near the bottom and allowing free circulation of the oil around it. The circulation is achieved by a stirring propeller in the lower end, and the calibration zone is located inside the inner tube. The heating power is supplied by two different heaters, one main heater wrapped on the outside of the outer tube and one placed in the space between the cylinders. The main heater acts as a guard heater and is supplied with constant power to give the outer wall a stable temperature, just below the set point. The second smaller heater performs the regulation with the aid of a commercial controller. The bath is housed in a floor cabinet and has a working space of diameter 100 mm and a depth of 500 mm. Temperature stability and uniformity achieved in the bath is around +/-1 mK in the whole range up to 200 °C, and this is without the use of any kind of equalising block. [12]

As the body of coolant in the Pilot Plant construction is required to be relatively large (100 litres), it was considered that the coolant should be circulated with a relatively high flow rate to gain an acceptable level of temperature stability and uniformity. The circulation idea came from an experiments regarding surface heat transfer in a stirred boiling-water bath and a precision thermostat bath of water circulation .A platinum resistance thermometer element was used to measure both temperature and heat transfer conditions in a stirred boiling water bath. The average heat transfer was affected strongly by stirring but only slightly by the boiling rate. For both room temperature stirred baths and stirred boiling baths, there were fluctuations about the mean heat transfer rate. The magnitude of the fluctuations increased with the stirring rate and fluctuations had periods of 1 to 2 seconds. [13]

The targeted temperature uniformity in this project is 0.1 degrees C; this is considered necessary in order to overcome problem of thermal expansion difference between reference and sample in the 0.1 micron tolerance range. For tolerances in the nano range(<0.1 micron), a more elaborate and expensive method of control may be required, such as that in the temperature controlled baths installed in the latest types of liquid crystal injection systems and burn-in systems. The latter systems have emerged from recent research work involving computer simulation methods for the investigation of heat transfer and fluid dynamics. A forced gas circulation system, that employs a fan or a blower, is often used in these advanced temperature controlled baths. [14]

The constructed Pilot Plant coolant temperature is stabilised to a temperature uniformity of 0.1 degrees C through the body of coolant, using a PT100 temperature probe, a commercial temperature controller and a 3.5KW heating elements installed in both the measuring tank and the temperature normalizing tank. A domestic appliance circulating pump was installed to circulate the coolant between the tanks to achieve this result. This construction was relatively inexpensive with an acceptable level of temperature control uniformity.

2.3.2 Commercial oil baths

A substantial amount of commercial oil baths exist throughout industry and before prototyping of the temperature control system commenced, these industrial oil baths were assessed to consider the possibility of an industrial oil bath installation. The research results show that the specification of the industrial oil baths on sale do not match the requirements of the project. Data for three commonly used industrial oil baths was taken from the manufactures' websites and shown below to explain to the reader what is available.

HAAKE C10-B3 Heating Circulator Bath [15]

The HAAKE C10-B3 3 litre heating bath is said to give simple, reliable options for obtaining consistent fluid temperature uniformity. The main task for this very small heating circulator is temperature control of instruments, such as viscometers, photometers, refractometers or small autoclaves and reaction vessel at different temperatures. It has a robust design using high grade stainless steel inside and outside the bath and temperature resistant polymer. The bath is equipped with dial indication with fine adjustment temperature control up to 100 degrees C with temperature uniformity of ±0.01°C.

Cole-Parmer Polystat Refrigerated Circulating Bath [16]

This bath is stated to be ideal for industrial or laboratory applications with a wide variety of temperature control requirements, and is available in 6-, 13-, and 28-liter tank capacities. Robust refrigeration system with metering control provides fast heat removal and stable temperatures. Industrial-grade circulating pumps deliver extra pressure providing more efficient heat exchange, better temperature uniformity, and improved reservoir agitation. Long-life high wattage heaters deliver fast fluid heat up for applications requiring rapid fluctuations. Standard digital-controller baths have a temperature limit of 150°C. Adjustable PID control provides stability of ±0.05°C. Water-tight touch-pad controls allow you to easily set temperature in °C or °F. Single-line LCD lets you continuously monitor fluid temperature in 0.1° increments.

LAUDA Aqualine Water Bath [17]

The LAUDA Aqualine water bath is available in five different sizes. All the baths are made from deep-drawn stainless steel, and do not have any fittings. In this way, the interior is used to its full advantage, and the number of samples per bath is maximised. The LAUDA Aqualine is orientated towards the requirements of biological, medical and biochemical laboratories and provides a temperature stability of ±0.05°C. The innovative casing concept of the LAUDA Aqualine unites design and robustness. The baths have neither circulation pumps nor any other fitting that makes them resistant to corrosion, easy to clean and disinfect and offers maximum usable space. This is advantageous for biochemical and medical use. The heating elements attached to the bottom of the bath vessel ensure a homogenous temperature distribution without spot overheating occurring even if large numbers of samples are to be temperature equalized.

Another example of a temperature controlled system is an invention which provides for the control of bath water temperature in a clinical analyzer to within tolerable limits. The following summary is taken from the patent application and led to some ideas for the prototyped temperature control system in this project.

Summary [18]: "The invention provides for the control of bath water temperature in a clinical analyzer to within tolerable limits notwithstanding changes in the ambient temperature level and notwithstanding the continuous transport of cuvettes containing liquid samples and reagent mixtures through the water bath for photometric analysis. The invention also provides control for the accurate regulation of bath water temperature in clinical analyzers, such control being implemented with little if any alteration in the existing analyzers. The invention provides a liquid bath temperature control which uses dual control loops to provide precise temperature control under all conditions and to achieve fast response without over-shoot or oscillation about the desired regulated temperature. In accordance with the present invention, a method of controlling the temperature of a liquid bath in a tank so that a desired constant liquid temperature is maintained substantially throughout the liquid bath, includes providing a heating element in heat transfer relation with liquid entering the tank at liquid inlet means, measuring the temperature of the liquid proximate to the heating element, measuring the temperature of the liquid at a point in the tank remote from the liquid inlet means, and energizing the heating element according to the measured temperatures obtained in the two measuring steps".

2.4 Automation Networks

The network for this project is required to allow the central controller to communicate with the associated machine controllers, and visa-versa. The communication consists of numerical values sent to the machine controllers from the central controller to signal the sample retrieval and machine parameter control. Upon request the machine controllers signal the central controller with a numerical value to represent the machine status (on/off). Because of the low level of data transfer required, the network chosen for the project is an AS-I fieldbus network. The AS-I network was also deemed very suitable, due to its' specifications, relative low cost of installation and user friendly application.

The AS-I system is suitable for lower levels of plant automation. It can stand alone or it can operate as part of a larger more complex system such as Profibus. The AS-I system brings a large degree of flexibility to modern plants and is now seen as the ideal replacement for the conventional cable tree architectures. AS-I is "The Simplest Automation Networking solution". It offers the lowest cost solution which is required in networking. At the same time, it provides power for the peripheral elements, transmission of data and diagnostic means throughout the whole system starting at the simple binary sensor up to the highest factory level. [19]

A technical description of the AS-I network and its' alternatives are outlined as follows:

AS Interface (ASI) Description

ASI: Actuator Sensor Interface is used to network sensors and actuators. AS-I is a two wire interface; Power and Data. Based around ProfiSafe [developed from Profibus DP].ASI bus was developed by Siemens Automation. The Topology may be Bus, Ring, Tree, or Star at up to 100 meters. Power is provided by a 24V floating DC supply, which can supply at least 8A over the network. The AS-Interface is an open standard based on IEC 62026-2 and EN 50295.

AS-Interface (AS-I) is the simplest of the industrial networking protocols used in PLC, DCS and PC-based automation systems. It is designed for connecting binary (ON/OFF) devices such as actuators and sensors in discrete manufacturing and process applications using a single cable. It is an 'open' technology supported by leading automation vendors. AS-Interface is a highly efficient networking alternative to the hard wiring of field devices. It is an excellent partner for fieldbus networks such as PROFIBUS, DeviceNet, Interbus and Industrial Ethernet, for whom it offers a low-cost remote I/O solution. It is proven in hundreds of thousands of applications, including conveyors, process control valves, bottling plants, electrical distribution systems, airport carousels, elevators, bottling lines and food production lines. AS-I is even available in a cut-down version known as AS-I SW for ultra-simple devices such as panel switches and indicators.

Industrial Ethernet Description [20]

The Ethernet interface is a cable bus which runs over copper or fiber. The copper interfaces use either a coax line or differential twisted pairs, while the fiber runs use fiber-optic cables. The Ethernet network is defined by IEEE 802.3. In addition to normal Ethernet signalling, IEEE 802.3af defines unused lines which supply DC power to peripheral devices. The Ethernet standard uses Manchester Encoding and Decoding. Access control is gained via Carrier Sense, Multiple Access with Collision Detect (CSMA_CD).

Preamble Field: A 56 bit pattern of alternating ones and zeros which are used to synchronize the receiver clock to the incoming data packet.

SFD Field: Start Frame Delimiter Field indicates the beginning of the frame.

Ethernet Packet

Ethernet Major Formats			
Protocol	**Frequency**	**Distance**	**Cable**
--	MHz	Meter	--
10Base-2	10	183	Coax
10Base-5	10	500	Coax
10Base-T	10	100	STP/UTP
10Base-F	10	1000	Fiber
100Base-T	100	100	STP/UTP
100Base-T4	100	100	STP/UTP
100Base-TX	100	100	STP/UTP
100Base-FX	100	--	Fiber

Table 2-3 specification of the major forms of Ethernet

Bit-Bus Description [21]

Bit-bus operates up to 62,5kbps, 375kbps or 1,5Mbps over a 120 ohm differential twisted pair cable using the RS485 interface [9-pin D sub]. Bit-Bus is used mainly for communication between programmable logic controllers (PLCs) and the main controller in manufacturing applications.

Optomux Description [22]

Optomux I/O units communicate with the host computer over an RS-422/485 serial communications link. Up to 256 individual units can be placed on a single serial data link for a total of 4,096 digital and analogue I/O. The cable consists of two differential lines and a ground [5-wire]. Optomux supports 8 baud rates of 300, 600, 1,200, 2,400, 4,800, 9,600, 19.2K, and 38.4K baud. Some boards [Brain Boards] also provide Ethernet ports for use on standard 10/100 Mbps Ethernet networks. Wiring is normally connected via screw terminals, but the host may use a 9-pin D connector.

ProfiBus Description [23]

Process Field Bus: (Pro-Fi-Bus) Based on the EIA-485 bus and EN-50170, using a non-powered 2-wire bus. The connection is half-duplex over a shielded, twisted-pair cable. The bus will use either a 9 pin D (DIN 19245). Data rates may be from 9600 to 12M baud, with message lengths of 244 bytes. At 12 Mbps the maximum distance is 100 meters. A maximum distance of 1200 meters may be achieved using a maximum data rate of 94kps. Up to 126 nodes may be connected in up two 5 segments, which are separated by repeaters. Each segment may contain up to 32 nodes which are laid out in a single node. Each node has one master and slave devices.

PROFIBUS is an open, digital communication system with a wide range of applications, particularly in the fields of factory and process automation. PROFIBUS is suitable for both fast, time-critical applications and complex communication tasks. PROFIBUS has a modular design (PROFIBUS Tool Box) and offers a range of transmission and communication technologies, numerous application and system profiles, as well as device management and integration tools. Thus PROFIBUS covers the diverse and application-specific demands from the field of factory to process automation, from simple to complex applications, by selecting the adequate set of components out of the tool box. Communication protocol at the protocol level, PROFIBUS, with the protocol DP (Decentralized Peripherals) and its versions DP-V0 to DP-V2, offers a broad spectrum of options, which enable optimum communication between different applications. Historically speaking, DP has been designed for fast data exchange at field level. Data exchange with the distributed devices is primarily cyclic. The communication functions required for this are specified through the DP basic functions (version DP-V0).

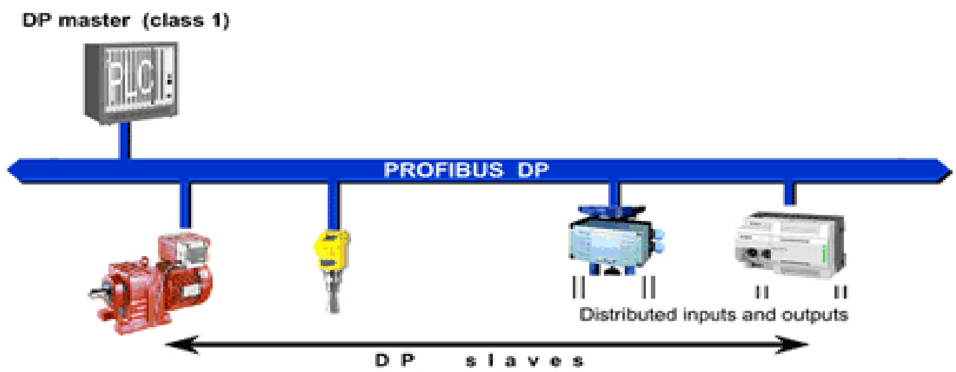


Figure 2-3 PROFIBUS DP

The basic DP functions have been expanded step-by-step with special functions, so that DP is now available in three versions; DP-V0, DP-V1 and DP-V2, whereby each version has its own special key features. All versions of DP are specified in detail in the IEC 61158. Version DP-V0 provides the basic functionality of DP, including cyclic data exchange, station, module and channel-specific diagnostics and four different interrupt types for diagnostics and process interrupts, and for the pulling and plugging of stations. Version DP-V1 contains enhancements geared towards process automation, in particular acyclic data communication for parameter assignment, operation, visualization and interrupt control of intelligent field devices, parallel to cyclic user data communication. This permits online access to stations using engineering tools. In addition, DP-V1 has three additional interrupt types: status interrupt, update interrupt and a manufacturer-specific interrupt. Version DP-V2 contains further enhancements and is geared primarily towards the demands of drive technology. Due to additional functionalities, such as isochronous slave mode and lateral slave communication (DXB) etc., the DP-V2 can also be implemented as a drive bus for controlling fast movement sequences in drive axes.

3 Component Handling

Introduction

This chapter discusses all aspects of component handling in the projects, starting with the pick and place unit which retrieves the sample components from the grinding machine. It explains in details the prototyping and construction of the component transfer air gun, the transfer piping system, the ball delivery system and the reference ball sorting system. All prototypes are discussed from the first design to the installed working model.

3.1 Pick and Place System

3.1.1 Design

One of the most difficult objectives in the project was to design and fabricate a system that could retrieve a random single ball bearing from an operating grinding machine in a reliable and efficient manner. This retrieved ball bearing then must be delivered into the ball propulsion mechanism for transportation.

The design of the pick and place retrieval system proved to be very difficult, due to the size variation in the ball bearings and their constant movement within the grinding machine turn table. The wall height of the machine turn table was another problem that would have to be overcome, as the surface of the balls within the turn table (See Figure 3.1) is significantly lower than this high side wall requiring an arm to reach both inwards and relatively deeply into the turn table bed. This allowed for the potential damage to the unit due to the fact that over 1 Tonne of ball bearings are continuously moving in circular pattern. i.e. Pushing something too deep into the machine bed could result in parts being bent or sheared off. Figure 3.1 displays a photograph of the balls within the turntable and the high surrounding walls.

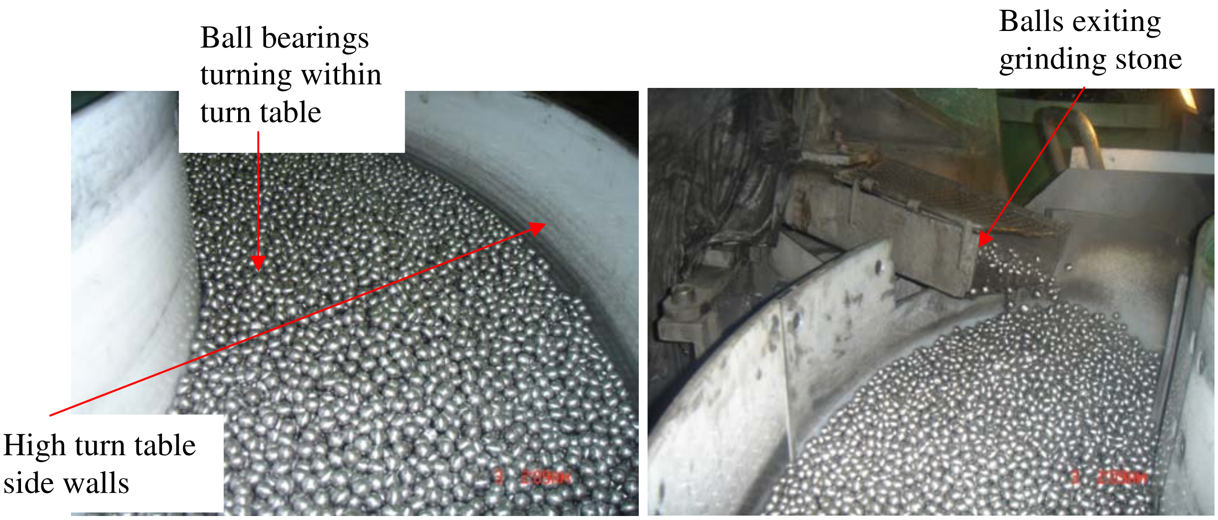


Figure 3-1 Photograph of Balls within turn table and high surrounding walls

The first idea for the system was to incorporate an electromagnet that would be made to pick up a single ball from the machine bed. The electromagnet could be placed on the end of an extendable arm reaching into the turn table. It was realised however that this method would cause residual magnetism in the ball bearing: this would result in problems later, as the ball bearings are checked for surface finish using instrumentation that is very sensitive to magnetic effects. After further consideration the following options were short listed and prototyped.

Option #1:

The first option to be studied was the use of a vacuum to retrieve a bearing. A ball would be lifted by a suction cup attached to a vacuum source.

Advantages:

- Suction is a clean method of retrieving the sample due to its enclosed method of transfer.
- No mechanical moving parts at the collection part.

Disadvantages:

- A vacuum source needs to be created and maintained continually.

Option #2:

The second option was the use of the turning action of the turn-table to move a ball into a machined slot positioned at the end of the retrieval arm when extended. When the ball is positioned in the slot a sensor would signal the retrieval arm to retract and deliver the ball to the propulsion system.

Advantages:

- Potentially fast and reliable method.
- Potentially robust system with simple control.
- Generic solution that can deal with all sizes of balls

Disadvantages:

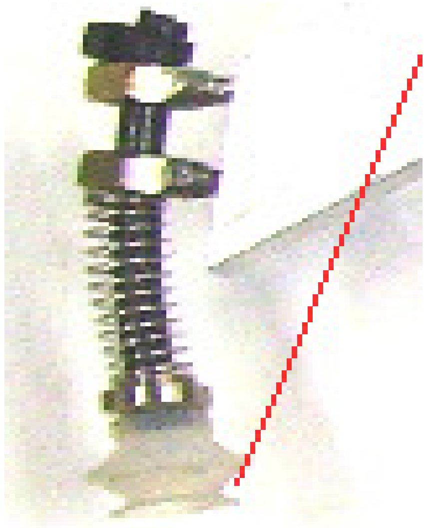
- There is much machining involved.
- It would be time consuming to prototype idea.

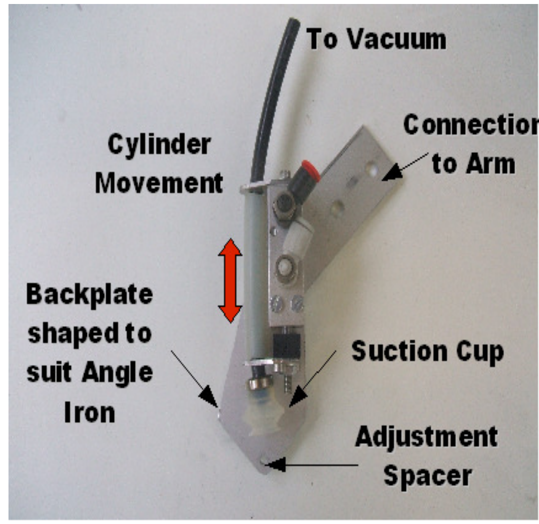
End Effecter Prototype #1:

As stated previously suction was considered as a viable option to pick the required ball bearing and a suction cup was simply mounted to the end of the arm with a spring allowing compliance in all directions if required. A vacuum generator was then set up to provide the required suction for this prototype test. As the testing was carried out in the laboratory at WIT and not on site, a replica of the machine turn table had to be put in place for testing. Through extensive testing, it was found that the random picking of balls was not reliable enough, possibly because of a lack of sufficient suction and a non-designated picking area. It was decided that this first prototype of a vacuum solution required rework and a second vacuum type was quickly fabricated. A photograph of this arrangement can be seen in Figure 3.2B

End Effecter Prototype #2:

For the second prototype, it was again decided that suction was a viable solution, but the method of implementation was reconsidered. A back-plate was fabricated and mounted to the end of the extending arm. A small pneumatic cylinder with a suction cup mounted on the side was then bolted onto this back-plate, as shown in Figure 3.2A. This provided the up/down motion for the picking of the ball when the arm was extended.


A



B

Figure 3-2 Suction Cup

As was learned from the first prototype, it was not reliable enough to just insert the suction cup into the moving mass of balls, so a track was designed from which to pick the balls. This consisted of a length of angle iron section being mounted at a slight angle of about 15° within the tank, just skimming under the surface of moving balls and lifting them out. The balls then travel up this track presenting one after another in a straight line, effectively running in the 'V' of the upturned angle iron section. A portion of the angle section was also removed at the end of the track so that the arm could not trap a ball bearing when it was lowered down into the angle section. In this instance the offending ball would simply be pushed out of the track by the motion of the arm (See Figure 3.4).
This design was rigorously tested, but yet again it was found that the reliability was not sufficient. As the arm extended the balls are still moving in the turn-table and the ball to be picked was not at an exact location. This made for unrepeatable alignment between the ball and the suction cup. If the suction cup was situated between two balls it sometimes would not function. The CAD drawing of suction cup components and assembly can be seen in Appendix B.

End Effecter Prototype #3:

For this prototype, the idea of using suction was abandoned. It was felt that suction was unreliable and an alternative mechanical method be sought. A CAD drawing and photograph of Prototype #3 can be seen in Figure 3.3.

The solution was to replace the vacuum cup by a spoon mechanism, which effectively acted as a cup that was big enough for only one ball to sit in, but the correct shape to accurately hold the ball during movement of the retrieval arm. A holding sleeve was fabricated, which would be situated within the 'V' section of the angle iron when the arm was extended. This sleeve was designed to accommodate one ball bearing only. The arm at this stage was tilted at a slight angle in order for the contained bearing not to drop out of the sleeve upon arm retraction. Detailed drawings of Prototype #3 end effecter are shown in Appendix C.

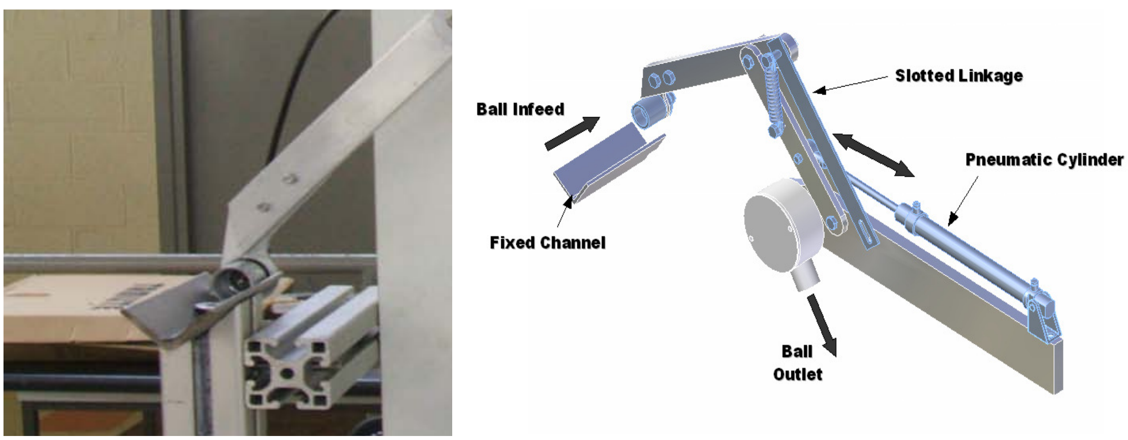


Figure 3-3 End Effecter Prototype #3

It was decided to use a small pneumatic pin cylinder mounted within the sleeve. This cylinder served not only to eject the balls, but also as an adjustable stop to ensure that only one ball would fit into the sleeve at any one time. As the arm reaches its retracted position, the ball bearing is ejected out into a 20mm PVC end-box mounted on the side of the arm. This standard part can then be linked directly to the propulsion system by means of 20mm flexible conduit. The system is shown in Figure 3.4.

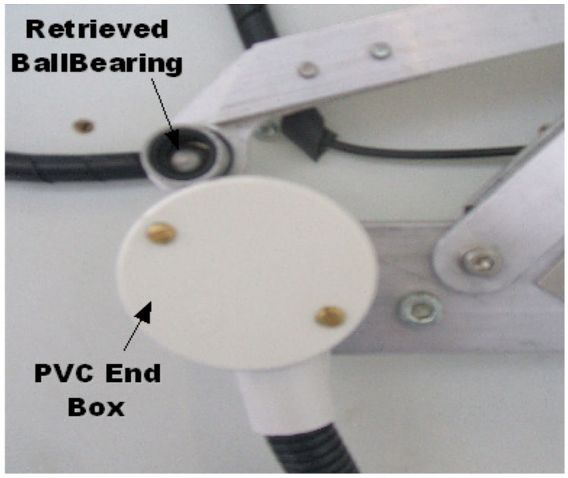


Figure 3-4 Installed P.V.C End Box

Decision

Both of these prototypes contained similar machined components and for this reason it was decided to produce a working model of both options and discard the lesser option upon results from testing. After testing it was decided that option #2 provided the greatest working repeatability and reliability.

Extendable Arm Design

All of the proposed end effecter design solutions needed to be placed at the end of a retractable arm and therefore this arm was the basis on which both prototypes were based. The initial design for the retrieval arm was to have an X, Y movement arm to effectively reach over the high sidewall of the machine turn table surface, however during proper-scaled drawings of this idea and a subsequent cardboard cut out it was realised that to achieve the required arm motion a very large and subsequently heavy arm would have to be produced. It was then decided to abandon such a construction and develop a more compact version that would possess the required movements.

From the general knowledge of mechanical linkages and systems it was decided to adopt a sliding linkage to a hinge-link arm in order to provide the double motion required. The sliding link operates by firstly allowing the arm to extend across the sidewall of the tank and stopping this primary arm motion in a designated point by means of a mechanical stop (See Figure 3.2). When this stop is reached the hinged mechanism allows the arm joint to increase and therefore provide the deep downwards motion required at the end of the cylinder stroke. The arm returns to its original position by means of a spring, which is installed under light tension insuring the slotted link, always returns to its original position. The force to extend the arm is provided by a double acting pneumatic cylinder. To prolong the life and reliability of the arm in operation two 19mm bearings are installed at the main joints of the arm. All CAD drawing of the arm construction are shown in Appendix A. A picture of this arm design is shown below in Figure 3.5.

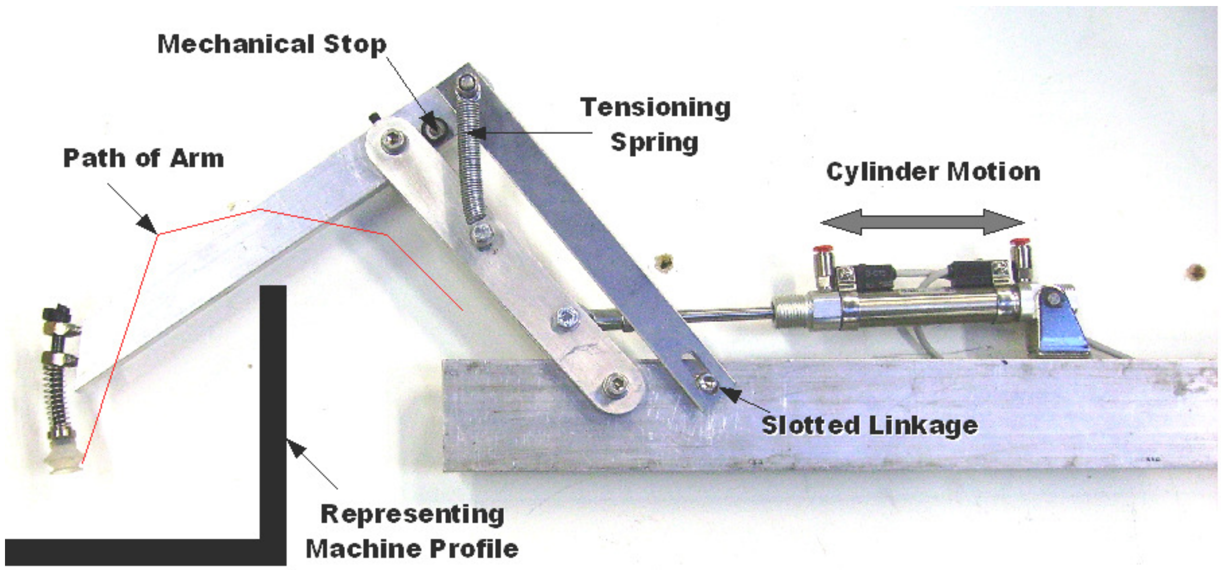


Figure 3-5 Arm assembly

Having produced the above design and incorporated a 100mm double acting pneumatic cylinder, the arm moved with too much acceleration and stopped too abruptly, resulting in a very fast operation that would possible, damage the surrounding balls upon arm extension. As a solution the existing cylinder was replaced with a 100mm cylinder with adjustable dampening cushions at either end of its stroke. Airflow restrictors were also applied to the ports on the cylinder to slow down its operation and so ensure fluent arm extension and retraction.

3.1.2 Pick and Place unit on-site installation.

Grinding Machine Retrieval Unit

When the prototype was developed in the laboratory it was thought that the retrieval system would be mounted from the side of the turn table. On arrival to the production plant this arrangement was reconsidered. The main issue was the need for the system to be discretely situated due to potential human interference from daily preventive maintenance. To achieve a fully functional and reliable system adjustment was made as follows:

1. Through a trial and error process the best location for the retrieval system was located on the external housing on the front of the grinding stone. See Figure 3.6. This was the most discrete location as it was not near any maintenance operations. It was also the most effective in terms of ball retrieval. At this point the balls form a single line formation and are moving faster than any other part of the turn table. This location is also directly behind the coolant distribution to the grinding stone; hence the balls are partially submerged in coolant at the point of collection. This creates less friction between the balls, and their movement towards the collection cup is improved. Because of this the ‘V’ section of angle iron in the turn table was not required and hence scrapped.

Figure 3-6 Installed retrieval system

2. The second alteration to be made to Prototype #3 was the installation of a sensor and blocker system to the retrieval cup on the end effecter. Figure 3.7 displays a photograph of the installed sensor and blocker to the end effecter. The addition of the sensor is to guarantee that the ball is in the cup at the end of arm retraction instead of relying perhaps on a less effective time out approach. The addition of the blocking pin cylinder is to retain the ball in the cup during movement. When the ball enters the cup the sensor sends a signal to the controlling PLC and the pin blocks the cup exit until retraction is complete and the ball is in a position to be released to the ball propulsion system.

Figure 3-7 Installed end effecter sensor and blocker

Lapping Machine Retrieval unit

As explained previously automation of two ball production machines was targeted in this project, one of which is in the grinding process and the second is lapping. After the Grinding machine retrieval system was installed and tested, some flaws were exposed. Even though it functioned well and the level of repeatability and reliability was excellent some changes could be added to the retrieval unit on the lapping machine, to decrease cycle time (approximately 1 second) and reduce energy consumption. The final prototype for the retrieval unit was installed to the lapping machine with the following changes and upgrades:

- The complete unit was constructed from stainless steel as opposed to the previous prototype which was made from aluminium. This would be a more robust design and therefore result in a longer working lifespan.

- As described previously, the sliding link operates by firstly allowing the arm to extend across the sidewall of the tank and stop it at a designated point by means of the mechanical stop. When this stop is reached the hinged mechanism allows the arm joint to extend and therefore provide the deep downwards motion required at the end of the cylinder stroke. The arm returns to its original position by means of a spring, which is installed under light tension ensuring that the slotted link always returns to its original position. By resituating the spring position and mounting it from the bottom of the sliding link as opposed to the top, the retrieval arm operated almost fully as a spring return system to allowing for a more fluent operating motion. See Figure 3.8.

- In the final prototype, the ram of the pneumatic cylinder in mounted higher on the extending arm to allow decreased torque in the extending operation and thereby reduce the air pressure required as well as the forces in the system.

- The angle at which the retrieval system in mounted on the lapping machine is changed to allow for gravity to aid the extension movement and to counteract the necessity for the up and down motion required to reach the balls in the turn table. By changing this angle there is more of a downward motion in operation. Figure 3.8 displays a photograph of the finished retrieval system prototype and the offset mounting angle of the unit.

Figure 3-8 Installed final prototypes of retrieval system.

3.2 Production Component Transfer

This section of the chapter discusses in detail the method of transferring the components from the machines on the plant floor to the measurement station. It includes the prototyping of the ball propulsion system and piping network between the machines and the temperature normalizing tank. Also outlined are the details surrounding the installation of the propulsion system and piping network to the production plant.

3.2.1 Component Transfer Air Gun

As part of the component transfer system it was necessary to develop a ball conveying prototype capable of transporting the sample balls in the range of 10mm-13.5mm, from the targeted grinding machine to the centralised measuring location. This system should be capable of transporting the ball relatively quickly without causing damage or inadvertently altering its properties in any significant way. A control signal would initiate the ball conveying and a sensor at the destination would signal its arrival. A generic system capable of transporting any ball in the current manufacturing range would be required as the production machines are not specific to one ball size. Experiments in the laboratory have shown that the method of using air pressure to propel the balls through an enclosed piping network would be both effective and reliable.

Design

Before the design of a propulsion unit system could be realised it was necessary to determine the size of pipe required to transport the full range of ball bearings. The largest ball in the range is 13.5 mm and the standard pipe with the closest internal diameter is 20mm pipe with internal diameter of 18mm. This piping was found to be large enough to allow the largest ball 13.5mm to easily travel throughout the pipe-work and navigate tight 90 degree bends, and experimentation demonstrated that it was satisfactory for the propulsion of the smallest ball in the range (10mm). The basic idea of a gun and breech mechanism was identified as being easily fabricated for a test prototype. The simple idea of a sliding breach and barrel mechanism with the capabilities of loading a single ball bearing and sealing the chamber after loading provided maximum thrust and no air loss. This idea also incorporated two rubber o-rings for an airtight seal, ensuring maximum pressure be applied to the ball bearing. Figure 3.9 displays a CAD drawing and photograph of Prototype #1. Full drawings of Prototype #1 are also available in Appendix D.

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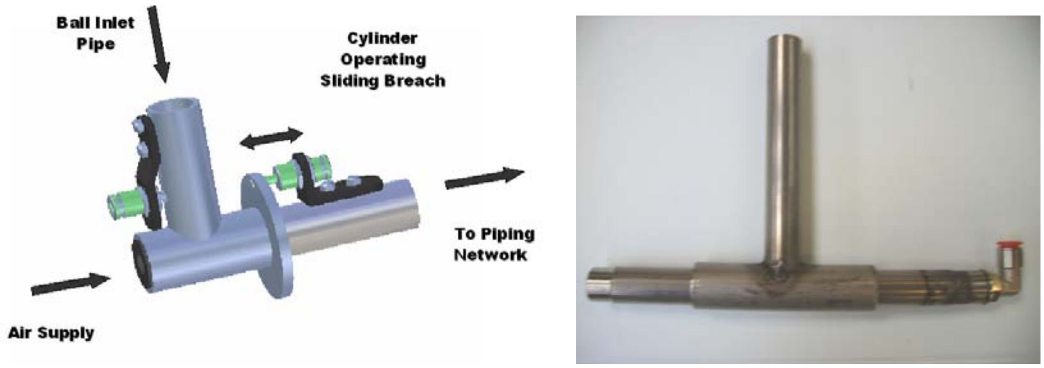


Figure 3-9 Mechanical Design and photograph of Prototype #1

To test this propulsion system the mains air pressure was attached and utilising a short section of 20mm plastic piping the power of the propulsion gun over the full range of ball bearings was sufficient. From this simple testing of the prototype it was found to have more than adequate power to propel any bearing in the current range (10-13.5mm) throughout the piping network. However upon testing of this device it was noticed that although the prototype operated successfully, the rubber o-rings incorporated in its design did show signs of wear. This highlighted the fact that the o-rings in this design could wear out and require replacement on a frequent basis, therefore increasing the cost of maintenance to the company and reducing the overall reliability of the system. A photograph of the incorporated O-ring seals is shown in Figure 3.10.

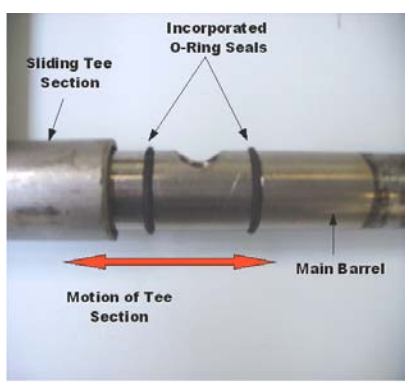


Figure 3-10 Incorporated O-ring Seal

The second prototype utilised standard parts to achieve its operation and only required a support bracket to be fabricated for the controlling pneumatic cylinder (See Figure 3.9). This reduction in machined parts results in a far less costly propulsion system when many replicas are required and also increases the reliability of the entire unit as manufacturer have extensively tested all standard parts used throughout this design.

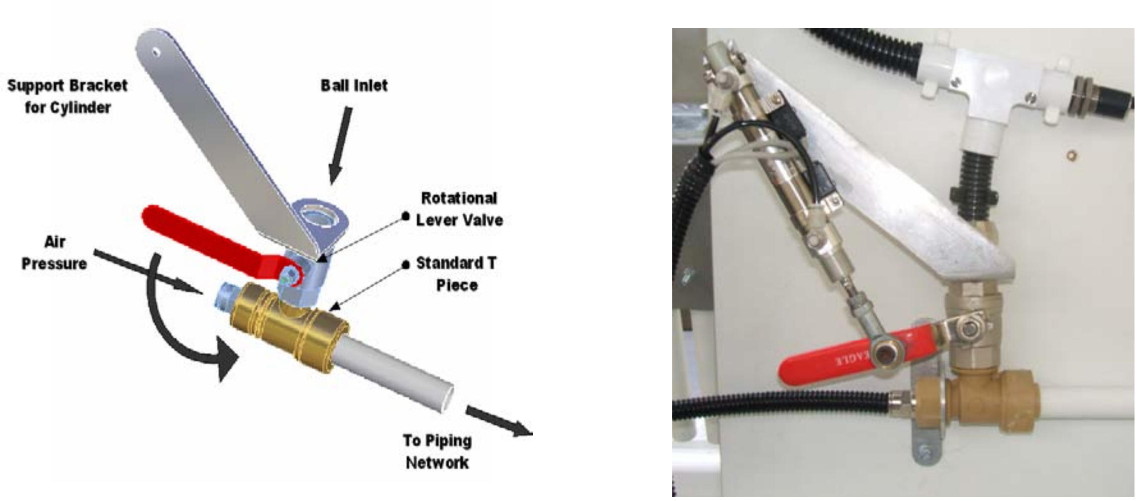


Figure 3-9Design Prototype #2

Having fabricated Prototype #2 from the standard parts chosen, it was tested on the piping network and its functionality was adequate. Having developed a working prototype and testing it by manually operating the ball valve it was now necessary to automate this process. The automation sequence was as follows:

- Open ball valve to load sample into the piping network.
- Close the ball valve to seal the chamber.
- Release the mains air valve to propel the sample through the piping network.

Initially the idea to use an automated 3-way ball valve (electrical operation 24v DC) to load and then seal the chamber was studied. This idea was quickly discarded however as it was found the lead-time for such a product was in excess of 4 weeks. It was also construed from analysis of the spec sheet that the valve might be difficult to modify.

Figure 3-10 Three way electrical ball valve

As an alternative an effective and more flexible method of automating the existing manual ball valve was developed. A simple linear pneumatic cylinder combined with the existing valve operating handle was installed as a means of opening and closing the ball valve. This option, it was felt, would provide the required movement and control whilst eliminating unnecessary additional cost during prototyping. If this prototype was successful a more expensive and reliable rotary actuator might be attached directly to the ball valve. Mounting this cylinder on the propulsion device required fabricating a support bracket. It was decided to attach two reed switches to this cylinder to check its operation and verify its movements. A photograph of the installed automation components can be seen in Figure 3.11.

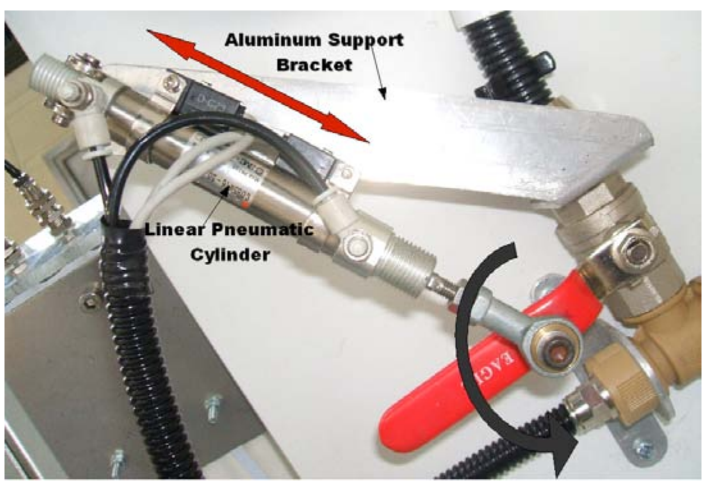


Figure 3-11 Automated ball valve

To propel the steel balls through the network a 3/2 valve was required for supplying the air flow to the propulsion system. A large throughput volume of air and not necessarily a very high pressure was required. Initially a smaller 3/2 valve was used to test the idea but was found to lack the required volume of air and substantially failed to transfer the sample to the measurement station. The solenoid operated valve with a 15mm diameter valve chamber was installed to the project. See Figure 3.12.

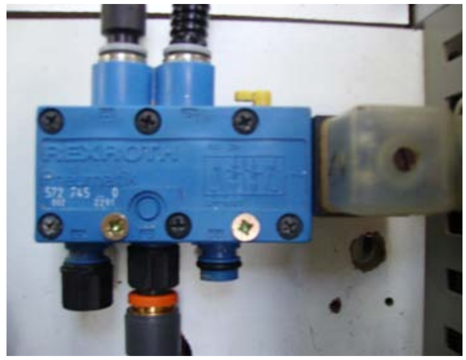


Figure 3-12 5/2 valve

The operation of this valve was controlled by a PLC. This PLC program incorporated feedback from an inductive proximity switch attached to the pipe-work to signal and count the steel balls as they entered the firing chamber and then trigger signal the propulsion operation.

After fabricating the chosen design for this propulsion system it was attached to the piping network created in the laboratory to simulate an onsite piping system (See Figure 3.16). After testing this system it was noted that the vertical speed of the ball up the piping network was directly proportional to the air pressure available. For example the 14mm ball bearing only required 3.8 Bar to lift the 5m and the 8mm ball bearing required almost 4.5 Bar to travel up the same vertical section of piping. Continued testing of the propulsion system for various ball bearing sizes produced different results in transportation time dependant on air pressure applied. (See Table 3.1). All tests carried out proved the design was functional and reliable in operation.

Process Name:	Minimum Sized Ball 8mm	Maximum Sized Ball 14mm
Retrieval System	11 Secs	11 Secs
Propulsion Device & Piping Network	9 Secs	7 Secs
Release Mechanism	5 Secs	5 Secs
Ball Sorting	6 Secs	6 Secs

Table 3-1 Summary of Propulsion Transfer Times

After testing of this prototype system in the laboratory it was decided to build a demonstration unit to demonstrate the control and operating features to the client company. As well as showing the performance of the system, this clarified the faultfinding and error detection of the system. The demonstration board also illustrated the physical size requirements of the unit i.e. A photograph of the demonstration board is displayed in Figure 3.13.

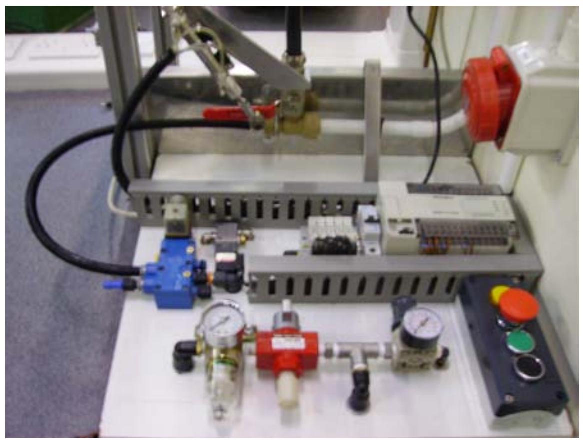


Figure 3-13 Demonstration Board for Propulsion System

3.2.2 Transfer piping System

The piping network was the third element of the transfer system and would transfer the steel balls to the measurement station and provide the required signals to the central controller upon delivery. The prototype network created in the Laboratory would attempt to replicate what would be expected in the factory environment.

Decision:

Although each alternative had a number of advantages and disadvantages, round plastic electrical conduit was chosen on the basis that it provided adequate protection to the ball bearing and is significantly easier to work with than its steel alternative. Other materials were also considered including hydradare piping and pneumatic airline tubing.

Having identified the material to be used, the first prototype of the piping network was constructed in the Laboratory. This prototype propulsion system would be used with this to determine what issues would emerge. A piping network consisting of eight 90 degree bends and a vertical lift of approximately 4m in height was constructed. A photograph of the plastic piping network is shown below in Figure 3.14.

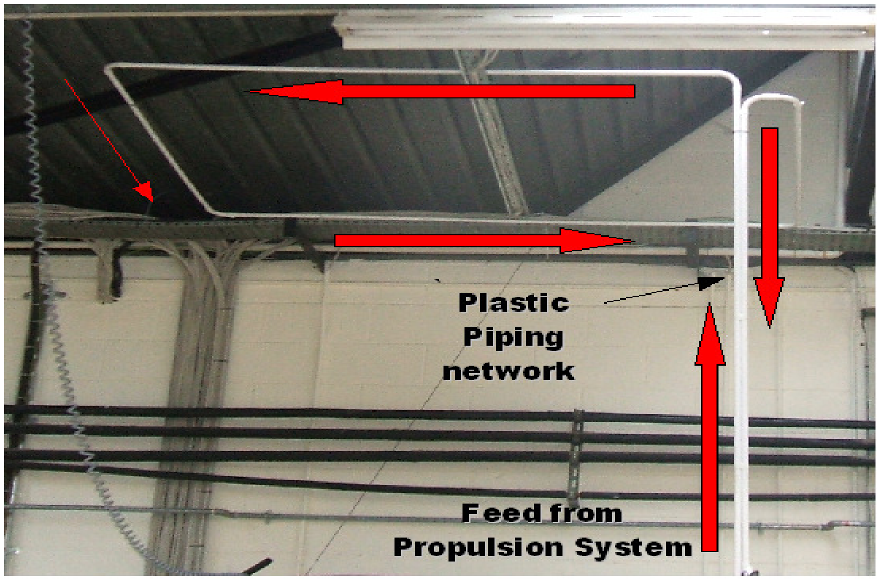


Figure 3-14 Piping Network Layout

On testing of the piping network it was found necessary to glue all parts together as the momentum and impact of the steel balls on the bends combined with the back pressure was sufficient to cause disassembly. A signal is required to inform the air gun that a ball had arrived and to stop providing propulsion to the piping network. To achieve this, a holding bracket was fabricated to hold an inductive sensor to the pipe near the end of the network. When a steel ball passed the sensor at that point it was thought the sensor would switch (See Figure 3.15).

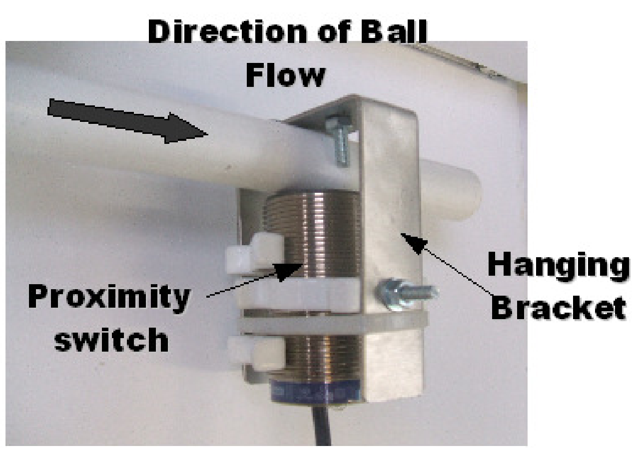


Figure 3-15 Proximity Bracket

Having fabricated and tested this bracket it proved to be unreliable in operation, as it was not sensitive enough to detect the balls travelling at high speeds (especially the smaller balls in the range). Further research into this problem revealed that the sensing distance of the proximity switch was not adequate enough for this application, coupled with the high speed of the passing ball bearing. The inductive sensor was replaced by one of a larger sensing distance (n=8mm) and reinstalled to the network. This proved more reliable than the original proximity switch but again not 100% reliable as required. The group assigned to testing the prototype decided to alter the shape of the actual piping network to manipulate the ball into making direct contact with the sensor therefore eliminating the issue of an inadequate sensing distance. A photograph can be seen Figure 3.16 of the redesigned prototype of the network where the sensor is used effectively as a stop to the ball bearing ensuring direct contact is made and a signal output obtained.

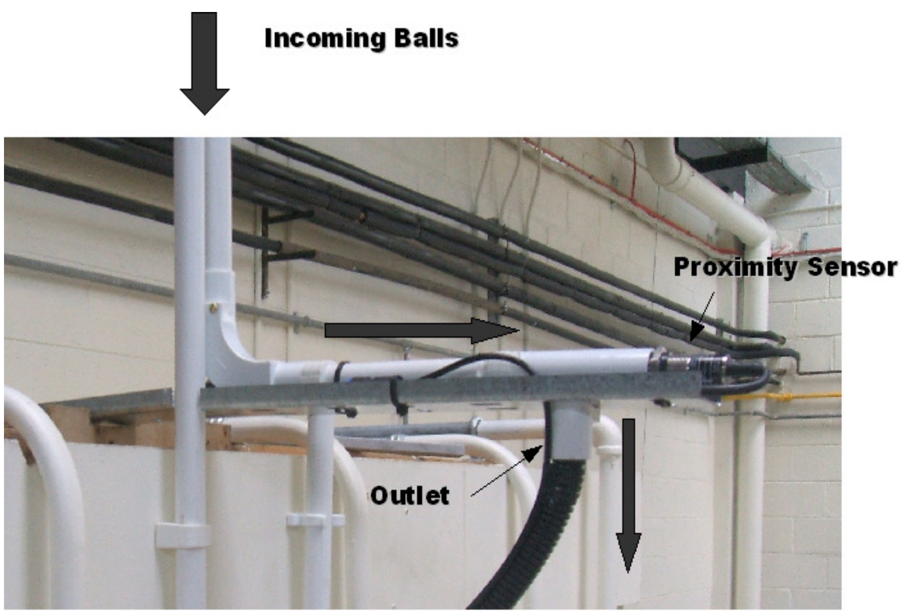


Figure 3-16 Dead End Stop Arrangement

The implementation of this alteration to the piping network also served another purpose as it resolved the issue decelerating the balls. It was important that the ball bearing enter the tank in a controlled manner so as to not upset the coolant and or disrupt its controlled temperature.

Consideration in design for maintenance issues are also present in this prototype as the end of the piping network from each propulsion system is fitted with a flexible section of PVC conduit approximately 500mm in length. This flexible section allows an end release system to be quickly and easily lifted in and out of the temperature normalizing tank for inspection or repair without undoing any fasteners or constraints on the rigid PVC piping. As previously mentioned the addition of an inductive proximity sensor to this piping network allows for tracking of ball bearings as they travel. The automation of the network works in conjunction with the propulsion system and one PLC program was written to automate both these systems and test their combined operation. A photograph of this installed section of flexible conduit is shown below in Figure 3.17.

Figure 3-17 Use of Flexible Conduit

An end release mechanism was developed to automatically release the sample balls at the point of measurement. The first prototype of this system was based on the stacking of the steel balls up to 8 high and releasing those balls one at a time after the cooling time has elapsed. The major technical issue associated with this aspect of the project is the stacking of ball bearings vertically in a queue and the periodic release of one ball bearing at a time as required. A reliable system of stacking steel balls in the required arrangement was not found during research. The main problem with the stacking of various size balls is that their diameters determine the height of the balls in the pipe. Such variation makes it impossible to use pins to constrain each ball bearing at predetermined heights, as the pins should be located in various different positions depending on the ball diameters used (See Figure 3.18).

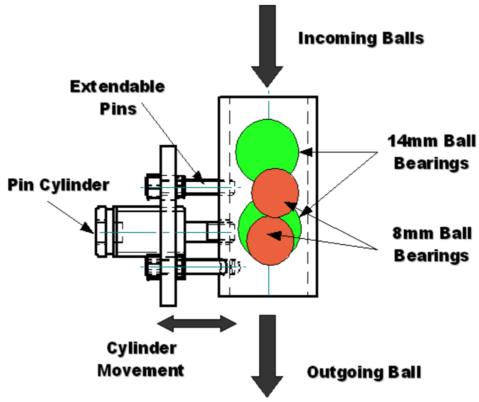


Figure 3-18 Pin Clamping

A second design centred on the idea of allowing the balls to support each other within the pipe is show clearly below graphically in the three-stage diagram Figure 3.19.

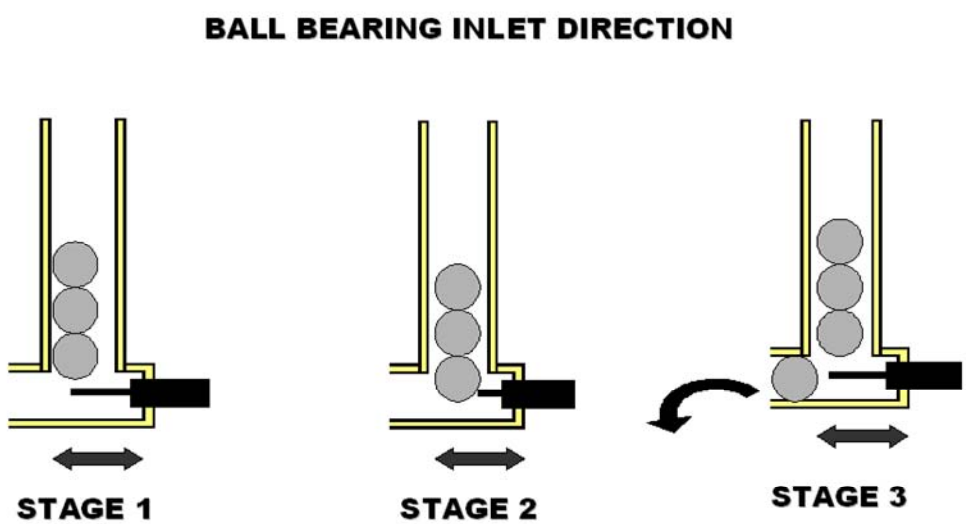


Figure 3-19 Principle of Operation

Explanation of 3-stage operating principle:

Stage 1: Balls queue in order of how the entered the holding pipe with the cylinder protruding and blocking off the outlet from the pipe.

Stage 2: The protruding cylinder retracts and all balls drop vertically downwards in a line with one ball now resting on the floor of the horizontal pipe.

Stage 3: The cylinder now extends to full extension pushing one ball ahead of it out the outlet and effectively resealing the pipe again.

This option was prototyped and its theoretical operation verified using a number of ball diameters. An added advantage of this meant that only one moving part was required and the reliability of the system is increased as a result. The CAD drawing and photograph of this prototype is shown in Figure 3.20. Detailed drawings of this prototype are also shown in Appendix E.

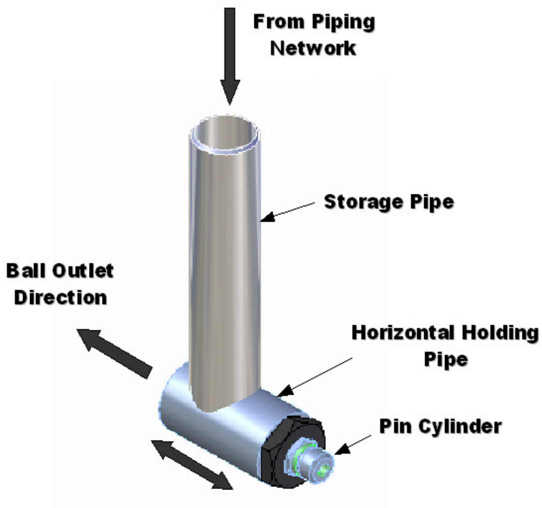


Figure 3-20 Mechanical design and photograph of Prototype #1

This initial prototype however proved to be too unreliable in how it released the balls. A problem with this prototype was that the diameter of the pipe was too large and sometimes allowed two balls escape at once. To address this problem three other prototypes were quickly developed and tested. Pictures of prototypes #2(a), #2(b) and #2(c) are shown in Figures 3.21.

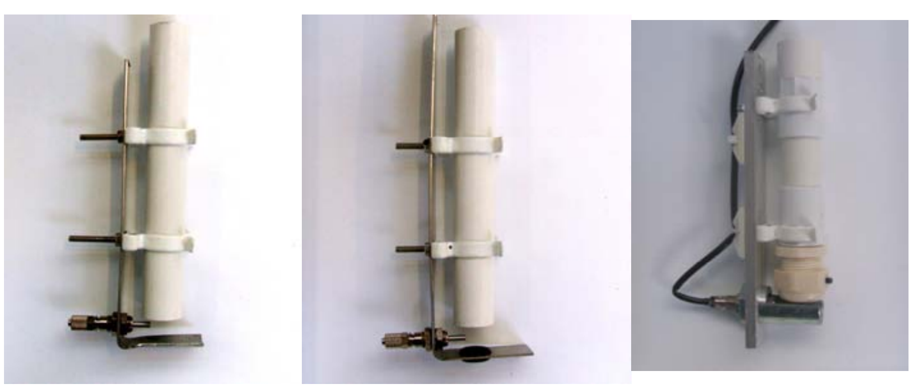


Figure 3-21 Prototype Ball bearing release mechanism

Prototype #2(a) offered a spoon shaped seat for the ball to land in and so support the balls queuing above it, therefore reducing the possibility of the second ball jumping free. Prototype #2(b) utilised a rubber grommet to effectively act as a seat for the ball bearing on the same principle as Prototype #2; although unlike Prototype #2 this idea ensured the ball be completely constrained in the actual grommet with the weight of queuing ball bearings holding it there. Finally Prototype #2(c) operated on the basis of incorporating a standard electrical 20mm gland with a variable diameter outlet that can be easily set to match the exact ball bearing it is required to release.

Having tested all three solutions it was found that although all 3 helped to reduce the problem only Prototype #2(c) acted with the required 100% reliability. The release units are inclined at an angle of 20-25 degrees to aid with the removal of balls from the unit by utilising the fact that gravity will hold them steady until physically pushed out of the unit.

As can be seen from the photograph in Figure 3.22, the end release systems are mounted on cross members (These are capable of holding 8 end releases units). These rails and a cross member were machined from aluminium and installed in the tank. An aluminium-inverted pyramid was fabricated to deflect all released balls quickly out through a single outlet of the temperature normalizing tank. Detailed drawings of these parts are available in Appendix F. The inverted aluminium pyramid funnelling system is clearly visible underneath the two end release systems in the photograph below.

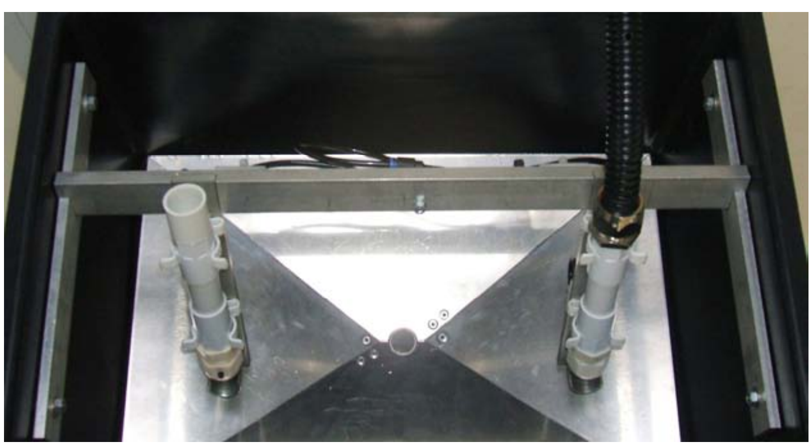


Figure 3-22 Installed end release units

3.2.3 Installation of propulsion and transfer system

After the transfer from the Laboratory to the on-site production facility the first task was to complete the installation of a functioning ball propulsion and transfer system. The task was to transfer the ideas put forth in the laboratory and adapt them to the real conditions on-site. Superficially these are outlined as follows:

1 Harsher working environment.
2 Increased number of test cycles.
3 Greater liability of mechanical damage due to human interference.

- Firstly, a more robust method of opening and closing the entry valve to the propulsion system was required because of the reason stated 1 to 3 above. In the previous prototype this was controlled by a pneumatic actuator mounted to a bracket and with the ram linked to the manually operated handle. Because of the increased liability of accidental human interference the propulsion system would have to be located in a discrete a location as possible. Also, minimising the number of moving parts was sought in order to increase system reliability.

- Secondly, the method of tracking the location of the components in the piping network and triggering the central controller when samples arrive at the measurement station had to be upgraded. As can be seen from Figure 3.19 there was a dead end stopping system in place to allow the samples to easily gravity feed into the temperature normalizing tank. At the dead end was the sensor to alert the system to the arrival of the samples at the measurement station. This sensing was difficult to do anywhere else on the transfer line as the velocity of the sample through the pipe was too great to be reliable. Although the sensor now senses the ball due to direct contact and also acts as a dead end to reduce ball velocity it has a very short working lifespan due to the impact the ball creates upon arrival. A better method of reducing ball velocity was required at arrival to the temperature normalizing tank.

- Thirdly, it was decided that the measurement station would be located away from the plant floor which was a significantly longer transfer distance than anticipated. It was thought that the same principles of transfer should apply no matter how long the distance. The only potential downfall was the height in which the network had to be installed as the existing cable trays, which were at double the height of the Laboratory set-up, were ideal to hold the piping network. Considering the layout of the machinery on the plant floor the installation of a lower level holding structure was not practical. A pipe was put in place to test the potential height limits of the transfer system. The test results confirmed that, using the existing cable tray and with as little pressure as three bars, the sample was delivered through the pipe work to the central location.

To address the first issue with the entry valve to the propulsion system a new rotary actuator valve was put in place. This rotary actuator was mounted on the concrete floor and directly attached to the existing valve. Upon command from the controlling PLC it would rotate 90 degrees and return to open and close the valve. This rotary actuator was essential as the propulsion system had to be as close to the ground as possible, as gravity feed was being used to transfer the balls from the retrieval unit to the propulsion system and the angle of decent was minimal. This prototype was much more compact and required no fabrication work to install. It was also a single component with no moving parts exposed which decreased the chance of inadvertent human interference. Above this automatic valve is a proximity sensor which sends a pulse to the PLC when a ball passes. This sensor allows the controller to signal a set amount of retrieval operation within a sample process. This sensor also triggers the opening and closing of the entry valve. Figure 3.23 displays a photograph of the installed rotary actuator.

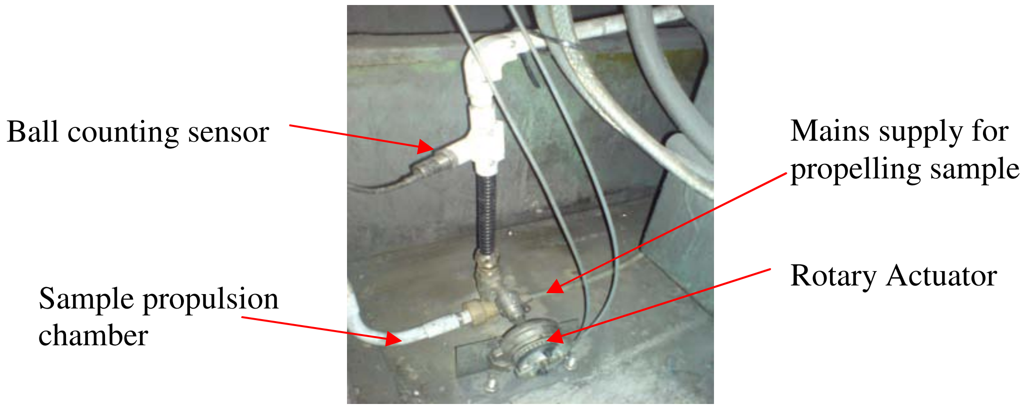


Figure 3-23 Rotary actuator

This automatic valve was installed with the propulsion system on the grinding machine and when a replica for the lapping machine was required, the system was prototyped further to create increased reliable in the system. When the prototyped automatic valve was proved to function well, a more expensive and reliable valve was installed in its place. This valve is operated via a 24 volt dc solenoid and is connected directly to the main air supply. It is a completely self-contained as opposed to the previous prototype which was connected to a solenoid valve chest. With this prototype the valve is attached to the pneumatic switching apparatus. See Figure 3.24 to view the contrasting differences between the new valve and the previous prototype shown in Figure 3.23.

Figure 3-24 24 volt dc solenoid operated valve

To address the second issue of decreasing the ball velocity as it reaches the central station a pipe meandering sub section was added to the end of the piping network. It consists of ten 90 degree bends within a close proximity of piping network. When the sample balls reach this part of the piping network it is only momentum which propels the balls to the temperature normalizing tank as the vertical pipe before the first bend is perforated. Although it is momentum alone propelling the samples at this point they are still at a high velocity. Each of the 90 degree bends at the end of the piping network dissipates some of the velocity and at the point of entry to the temperature normalizing tank which allows for slow moving samples on entry. The benefits of this are:

1. No abrupt stop in the cooling tank leading to damaged equipment.
2. As the samples are now moving slowly on entry to the temperature normalizing tank the sensors can be located at this point and function properly.

Figure 3.25 displays a photograph of the meandering section of piping at the entry to the temperature normalizing station.

Figure 3-25 meandering section of piping

3.3 Production Component Feeding to Measurement Station

3.3.1 Prototyped delivery system developed in the Lab

This section of the project concerns the ball delivery from the temperature normalizing tank to the measurement station. This entailed:

1. The release of the balls from the holding pipes in the cooling tank.
2. The synchronized operation of the main release valve from the cooling tank.
3. The stacking of the balls before measurement.
4. The injection of the balls to the measurement platform for measurement.
5. The guiding of both calibration and sample balls after measurement.

The primary design issue was to develop a method of moving balls into the measurement station. The first prototype idea was the concept a rotary indexer to move balls into position. The first issue to consider was that coolant may be used to maintain the uniform temperature of the balls during measurement as it was a comparative measurement. This would mean that the feeder device and measurement station would be partially immersed in liquid and therefore the device would have to be designed with this in mind. The idea of a four slot indexer was first suggested. The slots in the device were intended to allow the ball to roll out of the indexer, under gravity, to the measurement platform, (the intention being to mount the indexer on a slight incline).

As mentioned above, it was always the intention that the indexer would be immersed in fluid to cool the balls. This posed a limitation in terms of choice of drive configuration and other options needed to be considered but for the purposes of the first prototype it was agreed that the use of a stepper motor would suffice. After some deliberation, it was decided to stray from the original four-slot design to incorporate 16 slots as it was unknown how many balls would be queued at the stage of prototyping. The theory being that, with the addition of an absolute encoder on the driving motor, the position of a particular ball could be tracked around the indexer as the balls entered from the machines. A further advantage to having exactly 16 slots was that a stepper motor could be easily obtained to suit this number. Figure 3.26 displays a CAD drawing of the indexer arrangement. It was also intended that the measured ball would leave the measurement unit via the indexer.

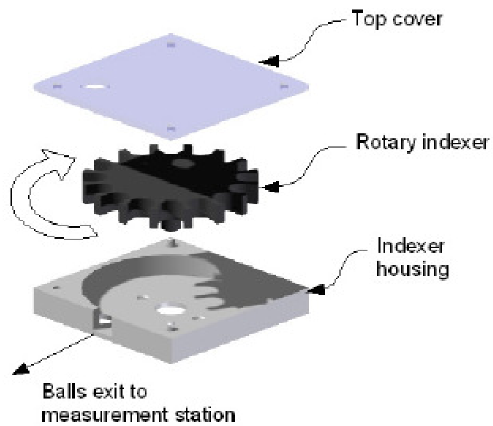


Figure 3-26 CAD model of indexer arrangement

Drive Methods

Many factors were involved in deciding on a driver for the indexer such as cost, availability, ease of implementation, and how well it suited the ball feeder mechanism. The main driver devices considered were a Geneva mechanism, a stepper motor, a rotary stepping pneumatic cylinder, one-way sprag clutches and a cam and sensors approach.

Prototype #1 (Rotary indexer):

The Geneva mechanism idea was rejected as time cycles are inherent in the design of a Geneva mechanism and as the cycle time for the measurement was not known the Geneva mechanism could not be designed accurately enough for optimum performance. Rotomation actuators were also considered but were rejected as to get them built to requirements would have been expensive. The sprag clutches idea which came from the same principle as the Rotomation had a long lead time and over complicated for the indexer. The stepper motor was the final decision to drive Prototype #1. With the 16-slot indexer, each slot was 22.5° so the stepper motor required would have to stop at every 22.5°. A 16-slot indexer along with the 7.5° step angle stepper motor (3 steps per indexer slot) stepping the indexer around to each individual slot was thought to be the optimum design for the ball feeding mechanism and was the final proposed prototype. Figure3.27 displays a photograph of the machine indexer and stepper motor (Prototype #1 of delivery unit).

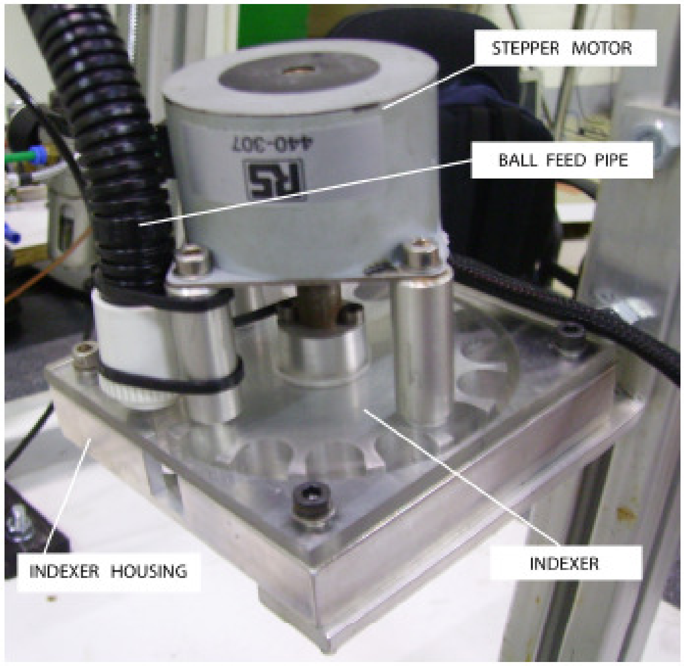


Figure 3-27 Motor arrangement mounted on bracket

To automate this prototype a PLC was used and a simple program was applied. The inputs were two optical sensors and start/stop buttons and the outputs were the ball release cylinder and the stepper motor. The indexer operates as follows:

Once the first optical sensor receives a signal indicating that it a ball is waiting in the ball release system it activates the rotary cylinder to turn the ball valve in the ball release system. The ball then travels into the indexer where it then arrives at the second optical sensor. This sensor sends a signal to the PLC, which activates the stepper motor to pulse 3 times to its specified angle. Once the ball is let out, measured and released, the second sensor once again receives the signal and the indexer steps to the next ball in the next slot. As long as the balls were constantly being fed to this unit, the program would continue to run until an error occurs (blockage, etc). For the stepper motor to function properly, it needed a clean 5V into the stepper drive board. To accomplish this, optical isolators were needed, as they would take in a voltage of 24V and give out a clean 5V to the board.

Prototype #1 Results and Conclusion

After rigorous testing of Prototype #1 it was deemed less than successful for a number of reasons:

- Lack of reliability due to frictional overload in the indexer. On occasion the 3 steps for one indexer segment were not delivered and the indexer would be misaligned (This of course could be overcome).
- If any more than one ball was at the indexer entry point the next step could not commence as the second ball would be partially caught against the housing wall entry point and the rotating indexer.
- As the project developed the design of the measuring instrument housing was ongoing. In the beginning it was thought that the measured balls would need to exit through the indexer due to a lack of space behind the measuring instrument. This was one of the main functions of the indexer. As the measurement housing design progressed, a space at the side of measuring platform could be incorporated with an alternative exit for the measured balls.

It was decided that the total amount of steel balls in the queue for measurement at any time would be seven. This consists of an upper and lower reference/calibration ball and five sample balls. After more analysis it was decided that such an elaborate design was not required especially since the idea of the measured ball leaving the measurement instrument via the indexer was dismissed. Because the balls could be stacked vertically a simpler strategy to deliver the ball one at a time could be developed. Prototype #1 was therefore discontinued.

Prototype #2 (Direct method):

The basis for Prototype #2 was on a more direct method of feeding the ball without an indexer arrangement. The main issue was to find a generic solution that would suffice for the range of ball sizes to be tested. It was easy to visualise a situation where a large ball would move through the device without a problem but if a small ball were to follow difficulty may arise.

The approach which was decided for Prototype #2 involved placing an incoming ball approximately 30 millimetres away from the measurement platform and then moving it into an exact position for measurement with the aid of a miniature pneumatic cylinder. In addition to moving the ball to the location position clamping the ball would also be necessary. The mechanism would also require that the balls be moved off the measurement platform. The simplest way to do this was to blow the ball off the platform with a low velocity jet of compressed air. These features can be seen in Figure 3.28.

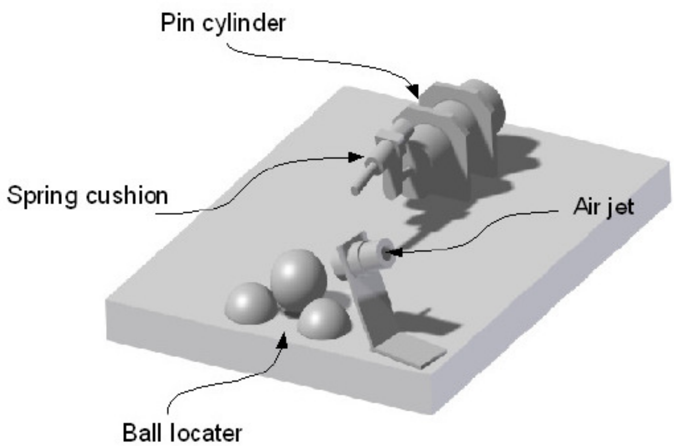


Figure 3-28 CAD model of the proposed direct feed method

The approach taken was to build a mock-up of the measurement platform and use this as a test bed for the new design. As can be seen from Figure 3.29, the measurement station used two balls sunken into a steel plate as a means of consistently locating the measured balls in the same position for measurement. This configuration needed to be replicated for testing.

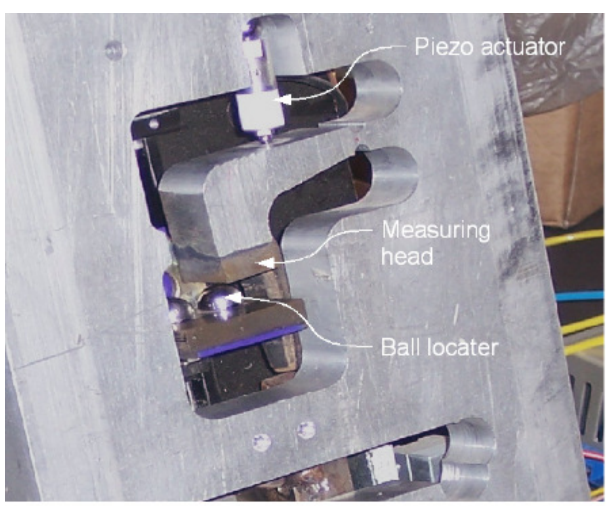


Figure 3-29 Piezo actuated measurement station.

Direct feeder construction

Initially, an anti-rotational cylinder with an adapted head was installed to push the ball into position for measurement. The adapted head would consist of a bracket with a prod that angled down to clamp the ball sufficiently while the ball is being measured. The problem with this design was that the variation of the balls would affect the clamping too much (e.g. The 14mm ball would be clamped properly but the 10mm ball would not). Obviously this method only suited one size rather than various sizes, so another design had to be developed. The new design consisted of a pin cylinder to push the ball into place and a separate clamping device to be incorporated to fix the problem in the variation of balls sizes. A gravity clamp was designed which would be opened using a second pin cylinder that had a hooked wire incorporated on it; the clamp and would fall back on to the ball under its own weight. The clamp was designed so that the pressure from the clamp would act on the upper half of the ball therefore providing a downward force on the ball eliminating the chance of the ball to be disrupted during measurement. The balls also needed to be brought away after being measured. An air jet was again used to blow away the balls. The issue of feeding the balls to the pin cylinder from the delivery pipes was then considered. A bracket was designed to hold flexible tubing and was positioned just in front of the pin cylinder. A sensor was also planned to be in this component to signal that a ball bearing is waiting to be fed into the measurement station. It was also thought that the pin cylinder pushing the ball out was not sufficient to keep to ball steady and moving in a relatively straight line. To combat this, a metal shoe was made to fit onto the pin cylinder and would keep the ball on a steadier path (Figure 3.30)

The fabrication for a working model consisted of:

- A bracket to hold the ball pushing pin cylinder.
- Guides for the ball being pushed out to the measuring instrument.
- A hook bracket had to be made and attached to a pin cylinder to bring the clamp up by force. The clamp could then fall under gravity down on the ball.

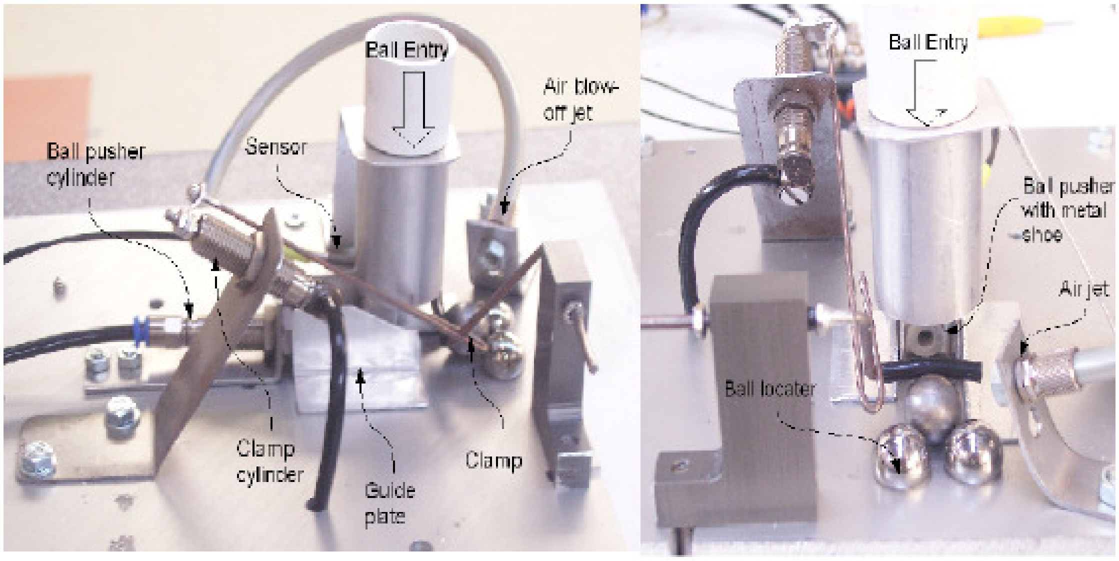


Figure 3-30 Elevation and End view of final assembly

Prototype #2 control

As with Prototype #1 one a PLC was used to automate this prototype. As there were even fewer inputs and outputs in this prototype a smaller PLC could be used. A photograph of this smaller PLC can be seen below along with the start/stop buttons and the air manifold.

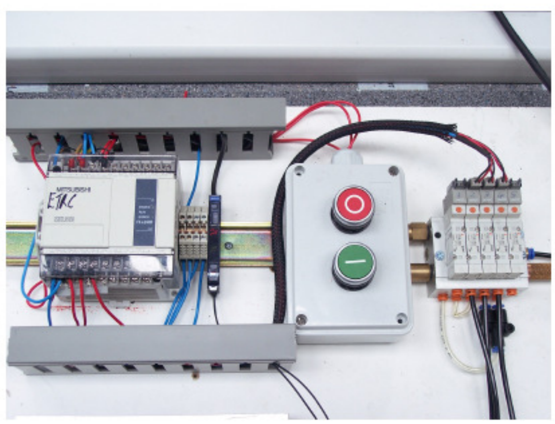


Figure 3-31 PLC set up for second prototype.

As the operation of the prototype would be signalled by the central controller, a start/stop push button was wired for prototype testing. Once this start button was activated the clamp would be raised to let out previous balls and the air blast would be activated to discharge the ball out of the measurement station. From there the pin cylinder would push out the new ball into the required position. The clamp would then be let down on the new ball to clamp in securely.

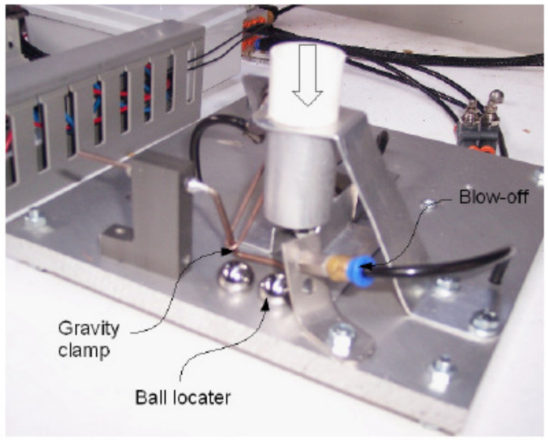


Figure 3-32 Final working model of Prototype #2

As can be seen from the Figure 3.32, the final working model of Prototype #2 varied slightly from the concept shown in Figure 2.28, the most notable of these changes being the clamping system. The implementation of the clamping technique proved to be more difficult than anticipated as positioning of the pivot was achieved by trial and error. It was determined early at in the design stage that the clamping force would need to have a line of action that would act close to the centre of the ball in a downward direction as this would provide the optimum constraint. The optimum position for the pivot was found to be just behind the ball locater, which ensured a consistent clamping action. This was important as varying ball sizes had to be accommodated and clamping had to be consistent throughout the range.

Key points:

- A method of clamping was achieved. The clamp opened by means of a cylinder moving a connecting rod, which opened the clamp. On release, the clamp would rest on the ball, holding it in place. Because the clamping wire was free to move within the connecting rod, this device worked for the range of ball sizes.

- An effective method of moving the ball into place was devised. Once a ball would drop down from the entrance it would sit on a chamfered hole in the base. From here a cylinder was used to push the ball up to the ball locater.

- An ejection system was implemented. By carefully positioning a small air nozzle to one side of the ball locater, a short blast of air could be applied to blow off the ball that had just been measured. As was mentioned before, this prototype was build to gain an understanding of the mechanics of the task at hand: it was actually the intention to blow the balls away with a jet of the same fluid that the devise would be submerged in.

- Reliable control was achieved. The PLC that controlled the device was able to execute a cycle each time the start signal was delivered without any faults.

Some experiments were conducted to determine how the device would perform under varying cylinder pneumatic pressures with different ball diameters, the results for which can be seen in the table below. The results gathered demonstrate some system reliability.

Prototype II tests					
Air Pressure (Bar)	Test no.	Cycle Time T_c (sec)		Clamping Success	
		14mm Ball	10mm Ball	14mm Ball	10mm Ball
4	1	5.95	5.65	+	+
4	2	5.97	5.79	+	+
4	3	5.97	5.73	+	+
4	4	5.8	5.89	+	+
4	5	5.99	5.63	+	+
	Avg.	5.936	5.738		
3	1	5.82	5.89	+	+
3	2	6.02	5.97	+	+
3	3	6.01	5.68	+	+
3	4	5.82	6.08	+	+
3	5	5.74	6.3	+	+
	Avg.	5.882	5.984		
2	1	5.94	5.77	+	-
2	2	5.85	5.69	+	+
2	3	5.89	5.89	+	+
2	4	5.74	5.83	+	+
2	5	5.74	6.13	+	+
	Avg.	5.832	5.862		

Table 3-2 ball injection Prototype #2 test results

The results detailed above show a cycle time of approximately 6 seconds. However, in terms of successful clamping, the results for the 10mm ball yielded one misalignment in clamping (see the 2 bar pressure test results on Table3.2). It was concluded that this was due to the fact that the smaller ball had slightly more compliance in the system thereby allowing it to misalign. Because of the level of results, the majority of basic concepts developed in Prototype #2 would be taken to the final installed prototype. The development of a third prototype, commenced after the design and fabrication of the measurement unit was complete.

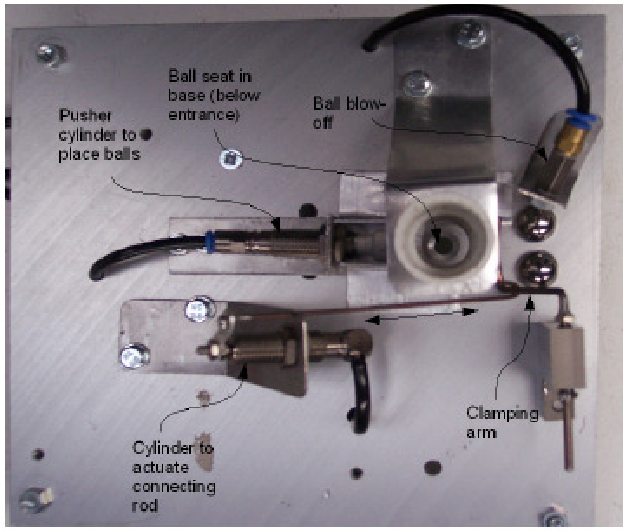


Figure 3-33 Plan view of prototype two final assembly

3.3.2 Delivery System Installation to the Measurement station

This installed prototype would function similarly to the previous prototype seen in Figure 3.33. The main issues were surrounding the fabrication of the delivery platform because:

1. The delivery platform could not touch or be connected to the measuring instrument frame because of sensitivity issues with the instrument.
2. The measurement platform is counter sunk into a plate of aluminium and the entry space around it is limited.
3. As the entry to the measurement platform is limited, the delivery system needed to be as small as possible. Also the visual and physical access to the measurement platform would be important for fault finding and observation of the critical measurement process: a large delivery structure would obstruct the measurement area and limit access.

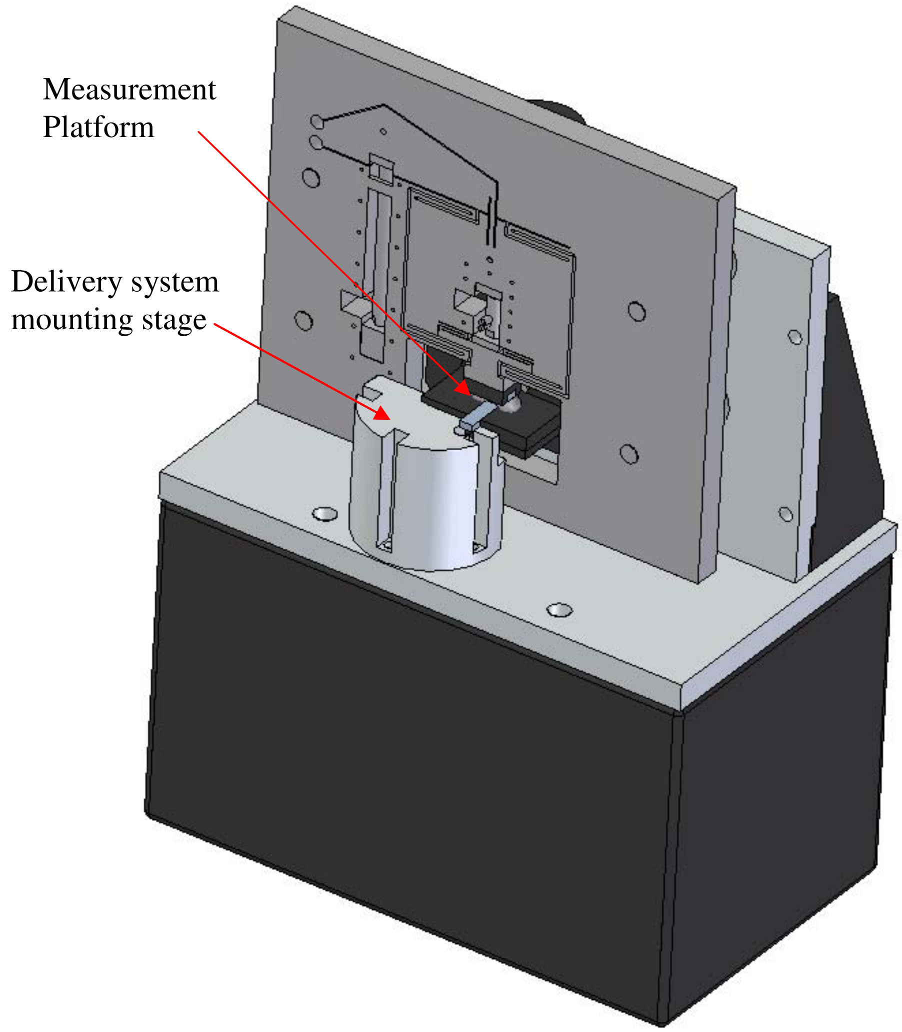


Figure 3-34 CAD drawing of measurement stage

The CAD drawing in Figure 3.34 shows the relative position of the delivery mounting stage and the measurement platform. The delivery system would have to align accurately in the X, Y and Z axes with the measurement platform to ensure a smooth and repeatable delivery operation. Up to this point, the main prototyping issued discussed in relation to the delivery system designs, have been related to the injecting of the steel balls into the measurement location. The complete delivery system is involves the release in the temperature normalizing tank, the guiding of the ball to the measurement platform, their removal from the platform and the separation of the sample and reference balls. Figure 3.35 displays a two dimensional diagram of the layout of the cooling and measurement station.

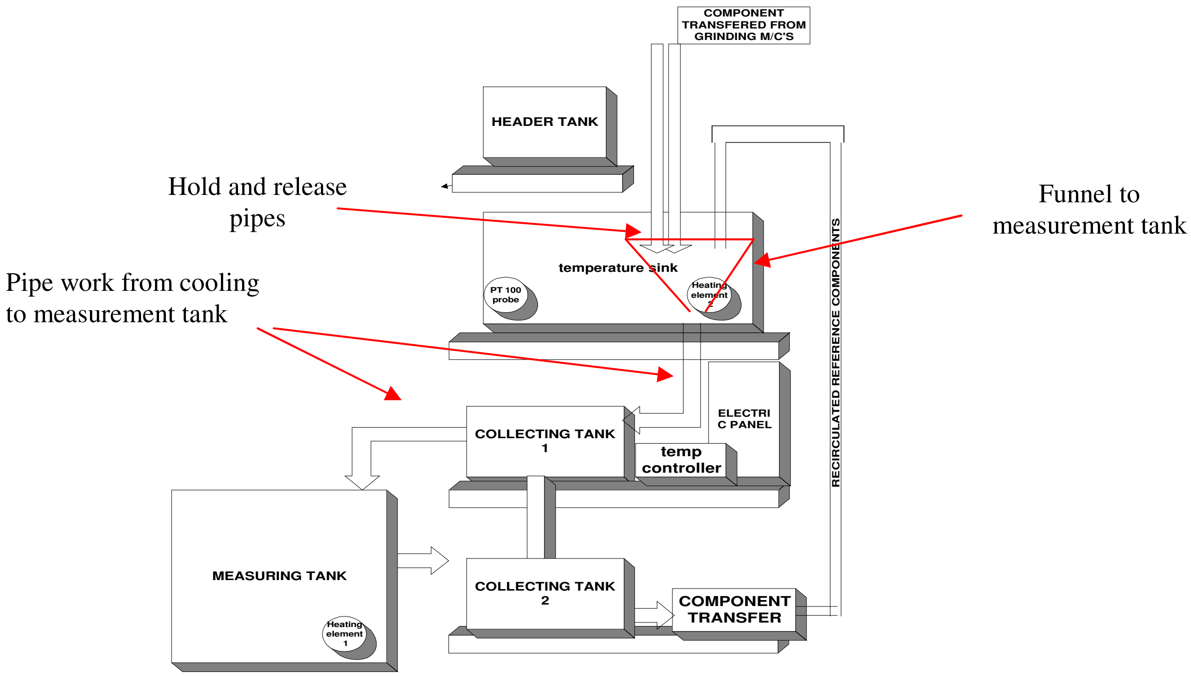


Figure 3-35 layout of cooling and measurement station

The complete delivery system operates in a series of steps as follows.

1. The samples arrive from the machines on the plant floor and are stored in their individual pipes in the temperature sink tank. Each pipe is fitted with a proximity sensor and before the balls arrive at the release stop where there temperature in synchronised, the sensor signals the central controller to start the cooling timer. This is the start of the delivery process.

2. When the cooling time elapses the central controller signals the release in sequence of the two calibration balls needed for the first sample and then the release of the first sample. The calibration balls and sample now sit in formation at the end of a funnel pipe, ready for the cooling sink valve to open.

3. The valve then opens and the balls are gravity fed to the measuring tank. As the balls are released a surge of coolant is released with then. This coolant is collected in the first coolant collecting tank: perforation in the transfer pipe allows the fluid to empty into the tank. The balls then arrive at the ball injection system without excessive coolant.

4. The balls are now sequenced, one to seven, in the injection system awaiting delivery to the measurement platform. At this point the central controller knows exactly what balls are in the injection system. The measurement process commences. The central controller now supervises the operation of measurement: the first ball is released, located, clamped and measured; as it is ejected the next ball enters, and so on, until the seven balls are measured. The measurements are then saved to a file.

5. The first two balls (the reference balls), are removed from the measurement platform and redirected back to their separate holding pipes in the temperature sink tank. The release is achieved with the help of a single acting cylinder at the end of a ball run-off slope (Fig 3.36), and a linear indexed distribution system will feed them into their respective holding pipes.

6. After the seven ball measurement sequence is complete the release of the next set of calibration balls and sample balls for measurement is signalled. This process continues until all available samples and measured. The central controller will then await the signal for the arrival of the next set of samples.

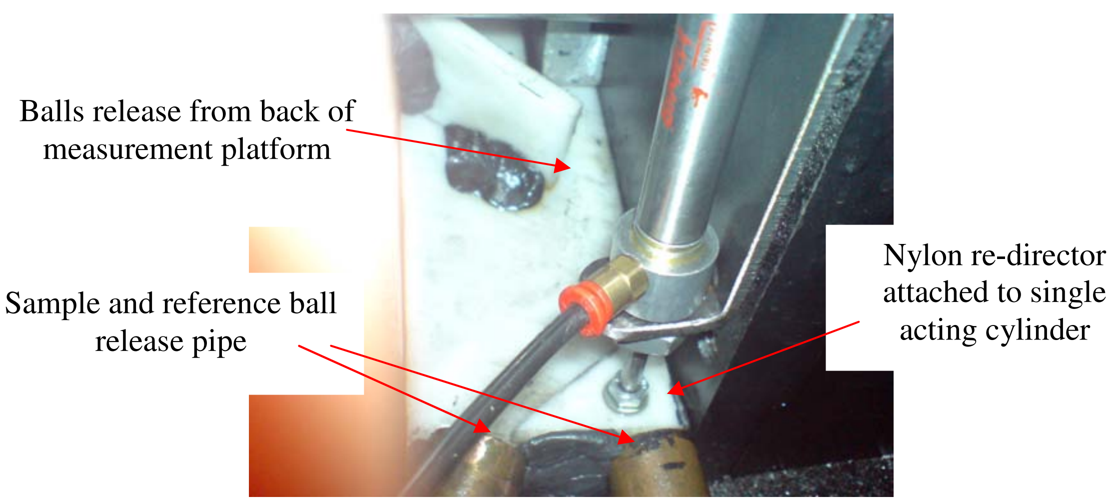


Figure 3-36 Ball run-off slope

The ball injection system

The ball injecting system, as implemented on-site was based on the design of the previous Laboratory prototype. The main difference was that the clamping device was removed. Through extended testing is had been deemed to be lacking in repeatability mainly due to the variation in ball sizes. The problem of consistently positioning the balls in the same location was overcome by stopping the inserted ball just before the measurement platform and allowing gravity to take it to this precise location when the loading pin cylinder in de-activated. This is done by simply inclining the complete measurement at an angle to create a slope on entry to the measurement platform. The simpler in-position gravitational source was to prove adequate for clamping during measurement process.

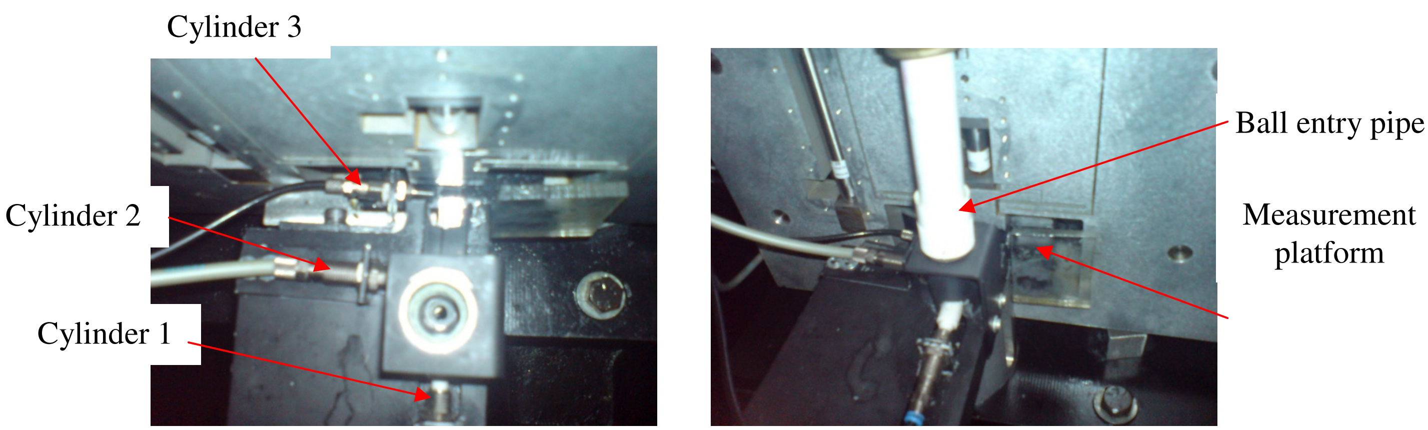


Figure 3-37 Side elevation and plan view of injection system

The injection system (Fig 3.38) therefore functions as follows:

The seven balls arrive at the injection unit, aligned vertically one after another, with the first ball sitting in a small counter-sunk slot in front of cylinder 1 and behind the extended rod of cylinder 2. When the measuring instrument is retracted, the central controller signals the insertion of the first ball. Cylinder 1 extends and cylinder 2 retracts simultaneously to insert the first ball into a slot concealed by cylinder 3 in front of the measurement platform. The function of this slot is to stop to ball just before the measuring platform. Cylinder 3 then retracts a half second after the ball arrives which allows the ball to gravity feed to the measurement location.

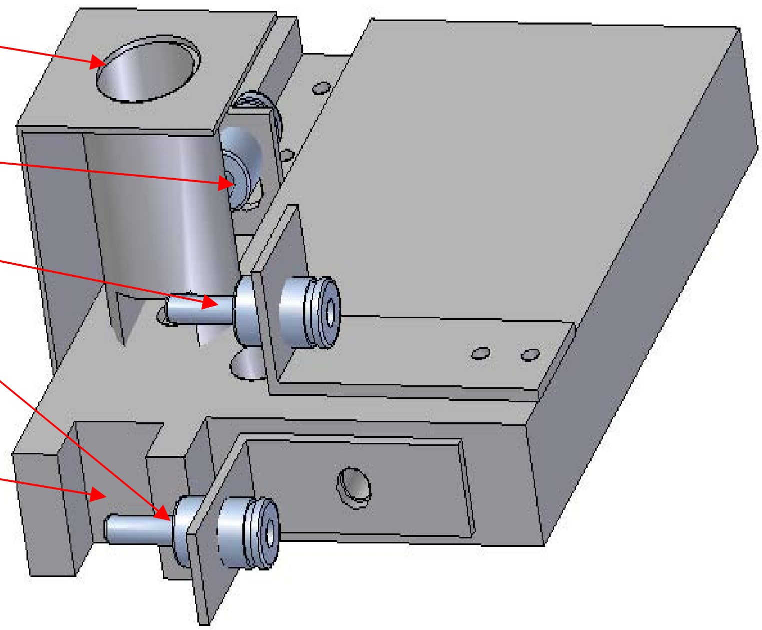


Figure 3-38 CAD drawing of ball injection system

The necessity to stop the ball before it moves towards the measuring location is mainly because the complete measuring platform moves vertically up and down on a lead screw. As the measuring instrument only has a range of approx 150 microns, the platform has to move to allow for the variation in ball sizes and get into the range of the measuring instrument(Fig 3.39). As the range of ball sizes is up to 4mm, the step from the injecting systems to the measurement platform can be up to 4mm. This difference creates issues as the higher the step from which the ball falls from, the greater the momentum generated and the faster the ball moves towards the measurement location. The more variation there is in the ball approach velocity the more difficult it becomes to consistently relocate to ball for measurement. To counteract this problem the seating surface of this slot is not connected to the injection system, but is a part of the measuring platform. Therefore, when the balls reach the step they are seated on part of the platform and as cylinder 3 retracts, the balls will move towards the measuring location at the same slow speed and will locate themselves against the twin spherical fixtures with what has been found to be good repeatability.

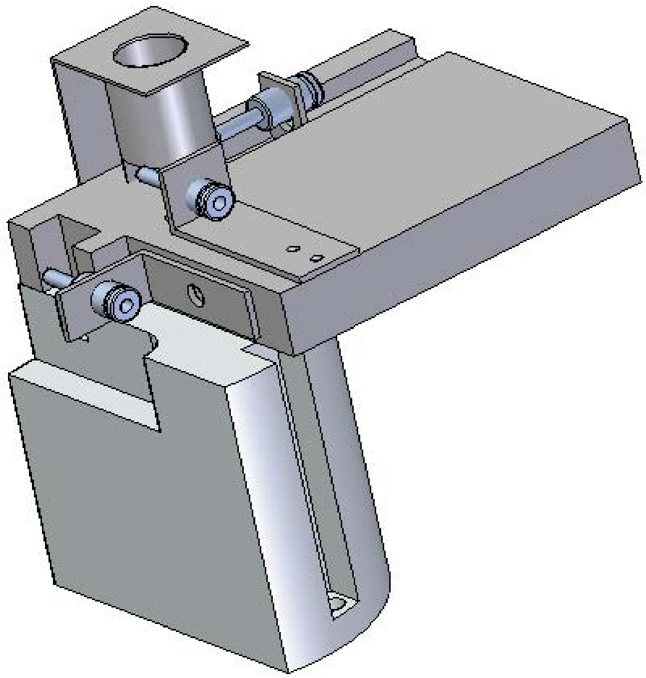


Figure 3-39 Concept drawing of ball injection system

After the first ball reaches the measurement location a reflective sensor detects if the ball if correctly positioned and signals the measuring instrument to extent the peizo for measurement. When the measurement is taken the peizo retracts and the ball is pushed from the measurement platform with a surge of compressed air. When this air surge is activated a signal to release the next ball for measurement is simultaneous set. This sequence operates until all seven balls are measured.

3.4 Reference Component Distribution/Sorting

This section of the chapter discusses in detail, the mechanical prototyping of a distribution/sorting system. The purpose of this unit is to relocate the calibration balls to their cooling pipes after the measurement has been completed. The control of the unit is also detailed.

3.4.1 Reference Component arrangement unit.

Introduction:

This part of the project requires the design and fabrication of a unit to separate and store standard/reference balls between measurements into predetermined holding pipes within the temperature normalizing tank. These standard balls are used as a reference for the measurement of the sample balls that are picked randomly from the grinding machine. The sorting cycle time should be as short as possible as it was felt there could be a high number of circulating standard balls within the system and a lengthy queuing time would not be acceptable.

The range of the measurement device is 150 micron and the maximum stock removal from the balls in grind is approximately 130 microns. Therefore, the measurement system only requires two calibration balls to set upper and lower control limits. So, for every sample ball size in grinding (for instance), two calibration balls are required with two individual holding pipes.

Option #1:
The first option considered was a rotating indexer mechanism similar to that used for the first of ball delivery prototype (Fig 3.27). The indexer would have a number of slots corresponding to the number different sizes of standard balls. Small pin cylinders would effectively release the ball bearing at the correct point on its cycle.

Advantages:

- Could accommodate a large number of different sized balls.
- Ability to work at high speeds.

Disadvantages:

- Extensive machining required.
- Expansion to accommodate more bearing sizes difficult.
- Complex control for high speed operation using stepper motor.

Option #2:
The second option was to machine a relatively complex slot out of a solid material to two different depths. This stepped slot provided two functions in that it would allow ball bearings to travel along its lower section and when required the ball bearings could be

lifted to its upper height and the machined outlet pipes could then be accessed. This design would incorporate a top plate containing one pneumatic pin cylinders per ball size. These pneumatic actuators are used to stop the ball bearing at a desired location. The bearing now in the correct position would then be lifted up to the awaiting pipe outlet just above its position and gravity would allow the bearing to roll out of the unit and into its particular storage pipe. An illustration of option #2 is shown below in Figure 3.40.

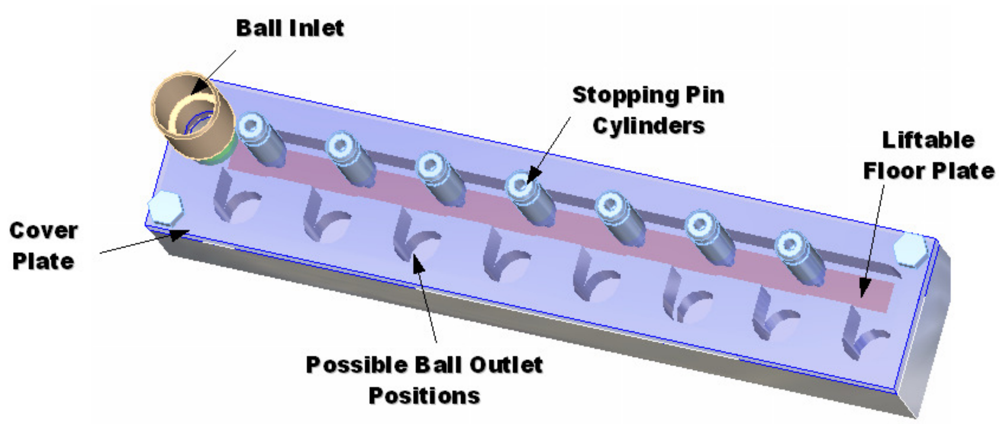


Figure 3-40 Design Concept Option #2

Advantages:

- Can be easily altered and extended by adding more modules.
- Simpler control (No electronics involved).
- Faster to produce and prototype than option #1.

Disadvantages:

- Large number of parts to be assembled (1 pin cylinder required per ball size).
- Moveable slot plate requires careful design and fitting.

Decision:

Option #2 was chosen on the basis that this method could be extended by adding more modules using existing CNC machining programmes. Requiring only the use of mechanical (pneumatic) controls option #2 seems a less complex and more easily serviced unit. It was also quicker and easier to fabricate. Having decided on design option #2, an initial prototype was then developed in accordance with the design shown in Figure 3.41.

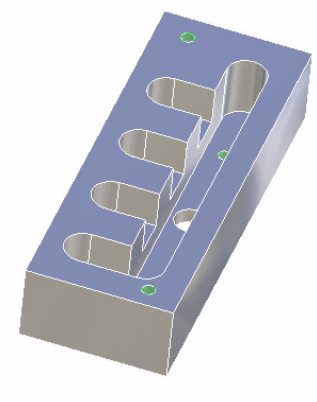


Figure 3-41 Machined Aluminium Block

A floor insert was fabricated from stainless steel and attached to the aluminium base unit in accordance with design concept #2. This movable floor was raised and lowered using two pneumatic cylinders mounted under the base unit. A transparent lid was fabricated out of Perspex and 3 single acting pin cylinders (to create a four ball separating unit) were rigidly mounted in precise positions. A picture of this fabricated top is shown below in Figure 3.42.

Figure 3-42 Perspex Top

When this initial prototype system was tested, it was found that when the two cylinders used to lift the track were activated, the steel track insert became jammed and would no longer freely move up or downwards. After extensive testing of this device the problem was revealed as misalignment due to non-synchronous movement of the two floor lifting cylinders. It was therefore decided that another method of lifting and lowering the floor plate would be required, resulting in Prototype #2. For the second prototype, a larger single cylinder was used to lift the track insert. This eliminated the problem encountered with Prototype #1: as it was much stronger and had a stiffer spring return force than that of the other cylinders used previously. A CAD drawing and photograph of the installed single acting lifting unit is shown below in Figure 3.43. Detailed drawings are contained in Appendix G.

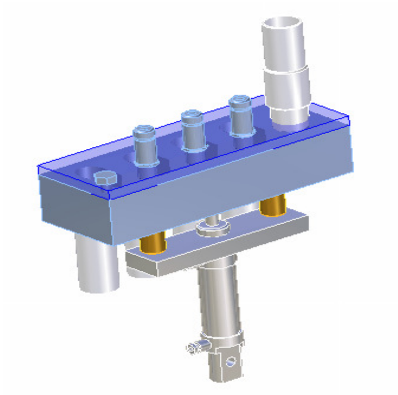
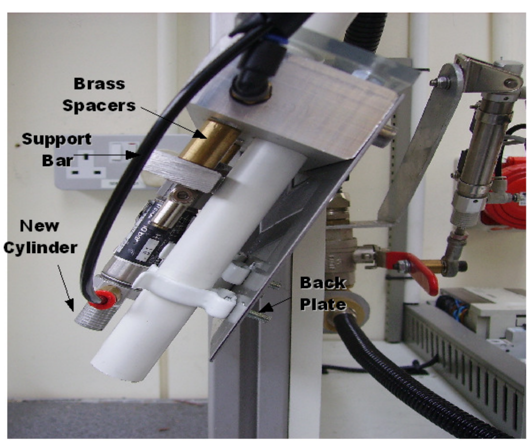



Figure 3-43 Mechanical design and photograph of prototype #2

As the complete measurement system was not at this point available, a moke-up of the control system was put in place to test the prototype. This final device would be controlled by the central controller and PLC, but to simulate this control for demonstration purposes a 3-position rotary selection switch was incorporated to effectively control where the ball bearing should be output, pipe 1, pipe 2, pipe 3 or pipe 4. This switch was connected to the PLC controlling this unit and a basic program was written to carry out the requirements of the system. After intensive testing, it was determined that this sorting unit was exceptionally efficient and reliable and operated equally well for each of the four outlet pipes. The jamming problem associated with Prototype #1 was no longer an issue. A side view to highlight the single acting cylinder can be seen in Fig 3.44.



Prototype 2 was installed at an angle when implemented to the demonstration board (approx 20-25 degrees off vertical) in order to ensure gravity carries the ball bearing out of the unit

Figure 3-44 Prototype #2 Installed

4 Temperature Normalizing and the Measuring Instrument

This chapter discusses the temperature normalizing between the sample ball and reference balls before measurement. This system was developed to avoid an offset in the sample measurement result due to thermal expansion. The construction of the Temperature Normalizing Pilot Plant is described. The measurement of the sample also takes place as this location: the design, development and construction of the measurement system, which is the focus of a separate Masters thesis is also outlined here.

4.1 Temp. normalizing of Reference and Production Components

Due to the dynamic nature of the measurement environment in the plant (potential temperature fluctuation, humidity, vibration, etc) and the micron level measurement required, a comparative approach to measurement was used (comparing the ball diameter with sets of minimum and maximum standard reference balls rather than absolute measurement of ball diameters). The objective was to mimic, as far as possible, the manual measurement process used successfully in the plant to date; targeting a measurement accuracy of one tenth (0.1 micron) of that achieved manually. An essential part of the measurement process was the comparative holding of the sample balls for a period of time in a liquid bath alongside the reference balls before measurement. The length of this holding time is approximately one minute (this timing was part of the 'Tacit Knowledge' of the measurement technician- experience has proved that it was adequate for the conditions in the plant). This chapter discusses in detail the construction of the pilot plant containing both the temperature normalizing and measuring tank and the method of regulating the coolant temperature between both tanks.

The linear thermal expansion coefficient relates the change in temperature to the change in a material's linear dimensions. In this project the metal components are being measured to an accuracy of 0.1µm Therefore, the difference in temperature between the sample and the reference balls must be considerably less than that which would increase/decrease the length of the component bearing by 0.1µm. The material from which the component is manufactured is 52100 chrome steel and the Coefficient of thermal expansion (α) for this material is 10.6×10^{-6}/degrees Kelvin. Working from the 0.1µm accuracy target, the allowable temperature margin can be calculated as follows for the 10mm and the 13.5mm diameter components:

Coefficient of linear thermal expansion = α.

Component linear dimensions =D.

The change in temperature = ∂T.

The change in length = ∂ L.

$$\alpha = \frac{1}{D}\frac{\partial L}{\partial T} \longrightarrow \partial T = \frac{1}{D}\frac{\partial L}{\alpha}$$

$$\partial T = \frac{1}{D}\frac{0.1\times10^{-6}}{10.6\times10^{-6}}$$

$$\partial T = \frac{0.00943}{D}$$

10mm Ball

$$\partial T = \frac{0.00943}{0.010}$$

∂T = 0.943 °C

13.5mm Ball

$$\partial T = \frac{0.00943}{0.0135}$$

∂T = 0.7 °C

Considering the largest component (13.5mm), therefore the maximum tolerable difference in temperature between the related balls would have to be considerably less than 0.7 °C. A target of 0.1 °C or less was set as the allowable temperature difference throughout the body of coolant (two reference balls and five sample balls are measured in rapid succession). The precise coolant temperature would be irrelevant but the uniformity of the temperature throughout the body of coolant (from the measurement tank to the temperature normalizing tank) should be controlled to less than 0.1 °C.

4.2 Outline of the Temperature Normalising Plant

The Pilot plant was developed in three stages. Prototype #1 contained one small tank and PLC. Its purpose was to determine the functionality of the equipment. It demonstrated the use of a circulating pump, the heating element, the PT100 temperature probe and its controller. This first prototype gave some insight into how Prototype #2 would function. Prototype #2 consisted of a five tank system; two collecting tanks (10 liters), a header tank (10 liters), a temperature normalizing tank and a measurement tank (both 80 liters) as shown in Figure 4.1.

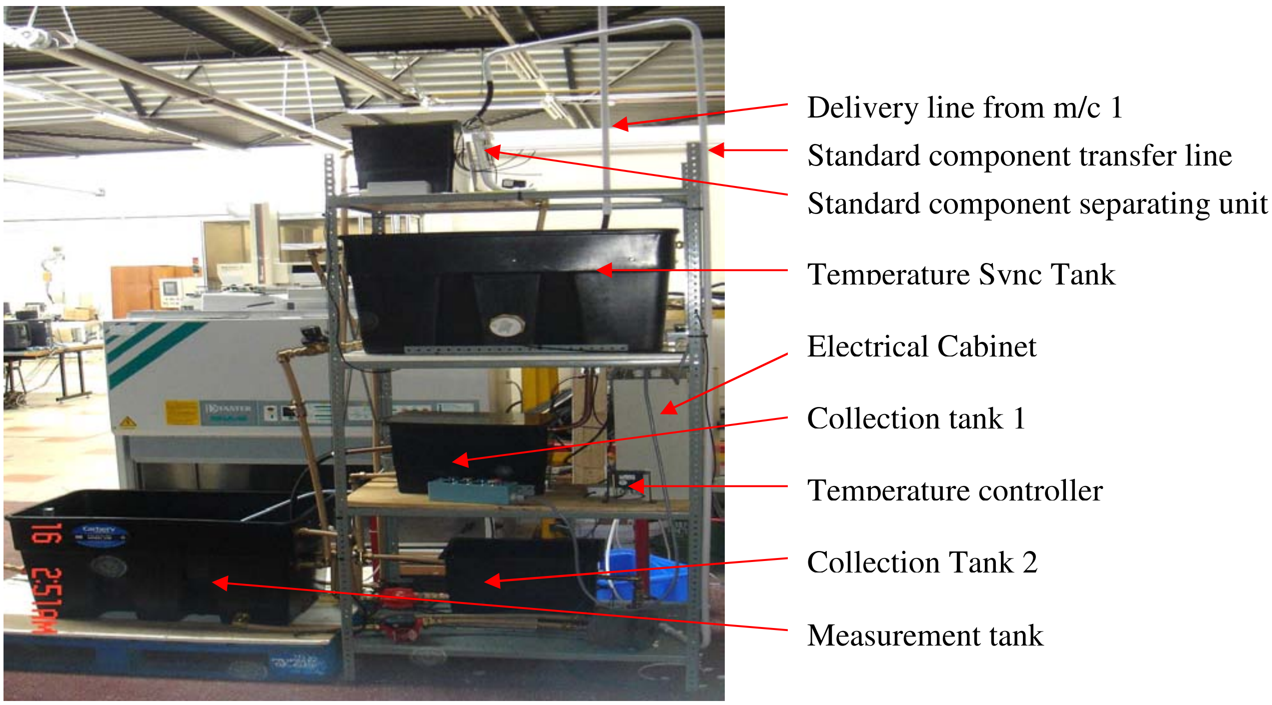


Figure 4-1 Constructed Laboratory Pilot Plant

This prototype was constructed in the laboratory to meet the on-line requirements as far as possible: this objective was that Prototype #3 would merely be an upgrade of Prototype #2. Prototype #2 was therefore designed to hold sample components from twenty machines, and well as catering for eight reference component size variations.

Prototype #3 was constructed on-site in the manufacturing plant (See Figure 4.2). The main alterations made were the adjustments to allow for the central controller to synchronize with the Temperature Normalizing plant PLC: this would link the measurement, normalizing, feeding and reference ball recirculation processes.

Repositioning of the measurement tank was required because of the sensitivity of the measuring instrument. A heavy cast iron platform was introduced as a base for the measuring tank in order to minimise vibration interference in the measuring instrument. This meant that the measurement tank had to be raised approximately 700mm. Because of this the coolant piping system was altered. As the head of pressure from the cooling sink to the measurement tank decreased due to the decreased height difference, the coolant circulation velocity decreased but it was found to be still satisfactory.

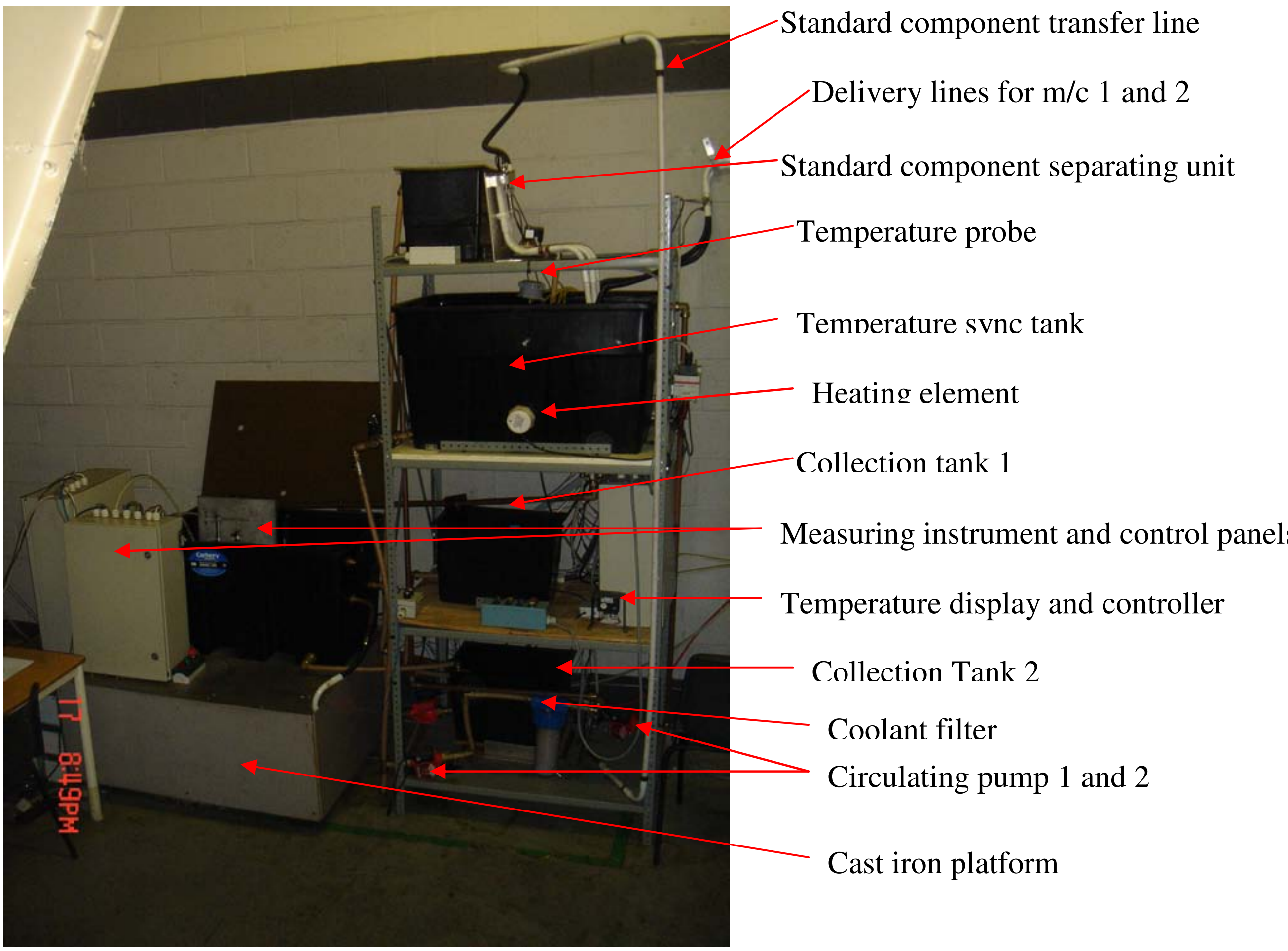


Figure 4-2 Pilot Plant (Prototype #3)

A coolant filtration system was also added to the Pilot Plant in Prototype #3. A schematic diagram of the Plant control cabinet is shown in Appendix L.

4.3 Temperature and Fluid Level Control

This section of the chapter details the construction and operation of the temperature normalizing process and how all aspects of the plant function.

4.3.1 Thermo dynamics of the plant

As the measuring instrument makes a comparison between sample components and reference components, the temperatures of the cooling tank and the measurement tank need to be equal. To achieve this, a 3.5KW heating element was installed in the temperature normalizing tank and in the measuring tank. Figure 4.3 displays a two dimensional schematic of the Plant and the ball piping system to the measurement tank.

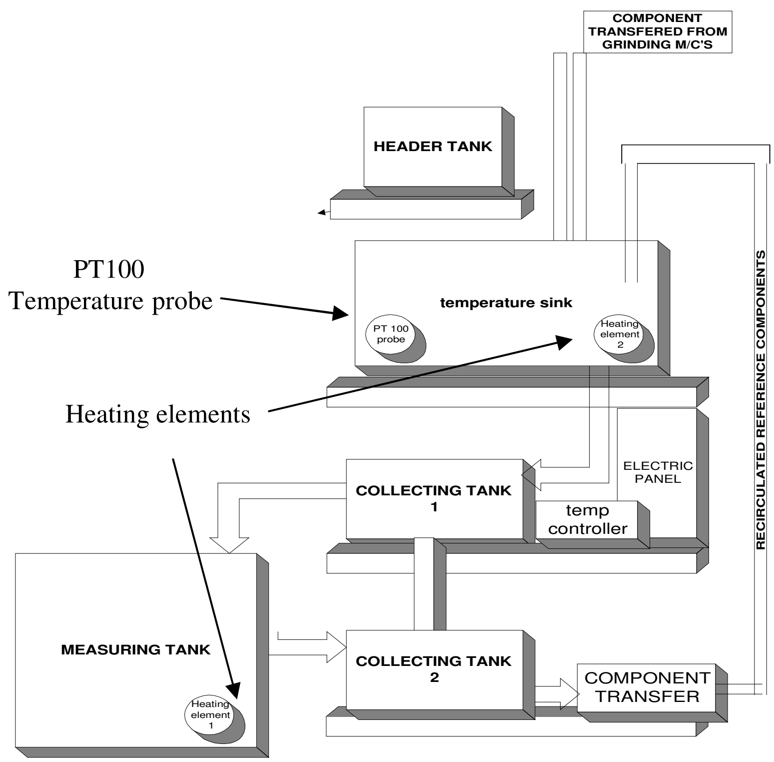


Figure 4-3 Thermo Dynamics of the Pilot Plant

The coolant temperature should to be as close as possible to room temperature to minimise the effects of the surrounding environment on the temperature normalizing system and thereby attempt to minimise the coolant temperature variations. Hot steel balls of course will bring additional heat to the system. The target fluid temperature is therefore currently set slightly above ambient so that the heating elements can be used to regulate it. The expectation is that the production ball will be cooled to this temperature but the heat loss to the atmosphere will be greater than this, so heating using and an electrical element will be required to hold the balance. As the quantity of production balls increases (as the system is expanded to include more and more production machines) the set points will have to be adjusted to re-balance the system.

A.

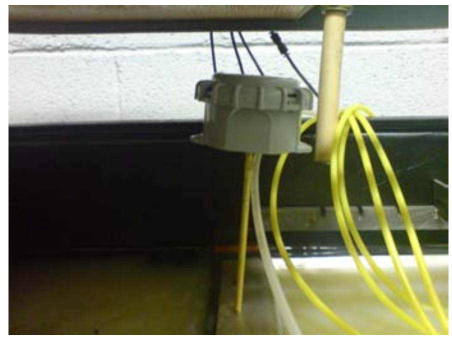

B.

Figure 4-4 Temperature Controller and Temperature Probe.

The temperature between the temperature normalizing tank and the measuring tank is maintained between two set points using a Carel™ controller (See Figure 4.4a). The controller receives a 4-20 mA signal from the PT 100 temperature sensing probe (See Figure 4.4B). When the temperature signal reaches the upper set point, the controller switches a 24 volt input to the main PLC and the heating elements are switched off. When the temperature drops to the lower set point, the heating elements are switched on.

In Prototype #2 the temperature probe was mounted through the side of the temperature normalizing tank. This method resulted in an inaccurate temperature reading as the compound used to seal the probe to the tank covered some of the probe rod and offset the reading. It was also difficult to secure the probe to the tank without leakage. In Prototype #3 this problem was resolved by waterproofing the electric circuit in the probe with a sealer and submerging the probe in a central position in the temperature normalizing tank. The probe could not be mounted from the top of the tank as the coolant level could vary slightly and the complete probe rod had to be submerged for an accurate reading.


A.

B.

Figure 4-5 Heating Element and circulating pump.

The 3.5KW heating elements are mounted through the sides of both tanks (See Figure 4.5A). The heating elements are located in the centre of the tank in an attempt to decrease the temperature variation in the system.

4.3.2 Fluid control of the Pilot Plant

Constant mixing of the fluid throughout the separate tanks of the plant was seen as essential in reducing temperature variations. To achieve this, the coolant is circulated constantly between both processing tanks. A high flow rate would minimise the temperature variation between them. However this high flow rate would have to be balanced against the displacement in the coolant which would affect the measuring instrument performance.

To create the coolant circulation a 20mm pipe, with a 24 volt solenoid diaphragm valve and a circulation pump (Fig 4.5B), was installed from the temperature normalizing tank to the measurement tank. When the Plant start button switch is turned on, the solenoid valve opens and the pump goes on stand-by and awaits a signal from the PLC when the level switch closes. To avoid overflow in the measurement tank, the flow rate into the measurement tank had to be less than the pumping rate of the circulating pump (the pump flow rate was adjustable so the flow rate could be arranged easily).

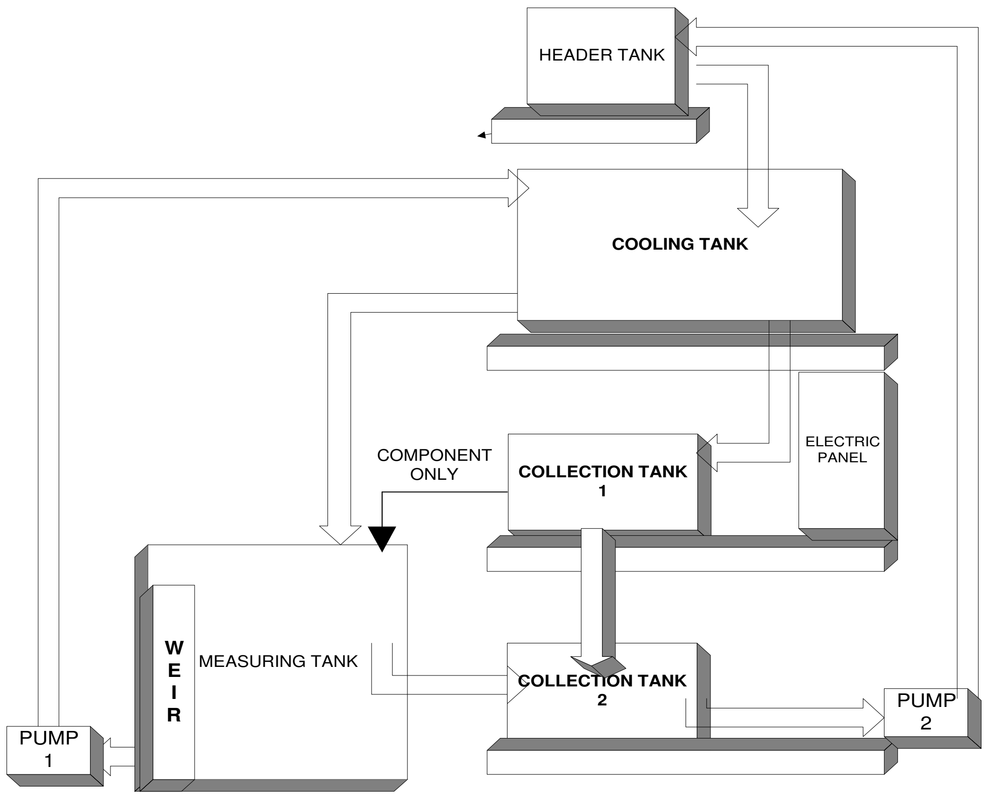


Figure 4-6 Fluid control of the pilot plant

For the measurement process the coolant level needed to be accurately controlled (a target of +/- 0.5mm was set) in order that the height of the fluid on the balls at the point of measurement was consistent. An overflow weir system (Figure 4.6) was introduced to achieve this. The flow rate and therefore the height over the weir, was controlled by adjusting the flow from the temperature normalizing tank. Without the weir system the flow rate in and out would have to be exactly the same to maintain a constant level. The weir was implemented as a separate smaller container within the measuring tank. The height of the container is the coolant level in the measurement section of the tank. The system worked as follows:

- The Plant is turned on which opens the solenoid valve.
- The coolant in the measurement tank overflows into the weir container.
- When the container below the weir fills, a level switch closes and turns on a PLC input.

- The PLC then turns on the pump for 30 seconds to empty the fluid.
- After 30 seconds the pump stops and waits for the weir container to fill again (the fluid in the temperature normalising tank constantly flows over the weir creating a constant fluid level).

4.3.3 Collection Tank 1

When the measurement instrument is ready to measure a sample the central controller signals the Plant PLC to release the sample from the relevant cooling pipe and open the main valve from the temperature normalizing tank (see Figure 4.7A). As the balls leave the temperature normalizing tank, coolant is released with them. The coolant is released out of the piping via a cut out slice it the pipe (Fig 4.7B), into Collection Tank 1 and the component continues to the measuring tank. The coolant is released to the collection tank in order to create as little displacement as possible to the coolant surrounding the measuring instrument. The collected coolant in Collection Tank 1 drains to Collection Tank 2 from where it is pumped back to the header tank. This pump is controlled by a float switch. When Collection Tank 2 fills, the float switch closes and signals the PLC to pump the coolant to the header tank for 30 seconds which partially empties the tank.

A.

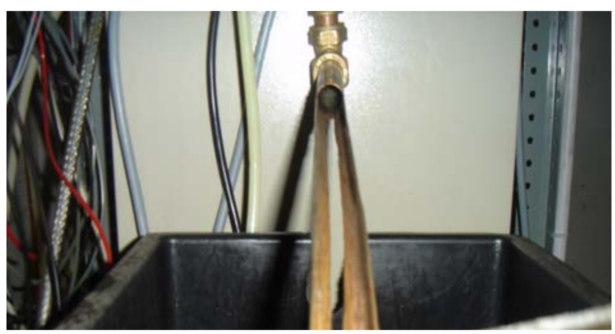

B.

Figure 4-7 Main valve and piping from temperature normalizing tank

4.3.4 Collection Tank 2

When the samples have been measured, they are ejected out of the system and the standard reference components are recycled back to the temperature normalizing tank where they are cooled again to the required temperature for the next measurement. A quantity of coolant will be released from the measuring tank with the reference balls. As the piping runs through Collection Tank 2 the coolant is released and the standard components continue to the transfer system for re-circulation using the same method as seen in Figure 4.7B. As mentioned in Section 4.3.3 this tank also takes the overflow from Collection Tank 1 and pumps the combined fluid back to the header tank.

4.3.5 The Header Tank

The function of the header tank is to maintain a reserve of coolant for the system and receive the coolant from Collection Tanks 1&2. The header tank regulates the level of coolant by refilling the temperature normalizing tank via an automated solenoid valve. (A level switch in the temperature normalizing tank signals the PLC to open the header valve; when the temperature normalizing tank refills the level switch closes and in turn signals the closing of the header valve). Because of the header tank, there is always enough coolant in the system to maintain the coolant levels and cater for all the losses from the system. Figure 4.6 illustrates the coolant flow within the Plant. From the grinding process to the release from the measurement tank, the sample ball generates and looses heat energy at different stages of the process (approximately 50 degrees C in the grinding machine to whatever the temperature normalizing system is set to). The flow chart in Figure 4.8 displays where the heat energy of the sample and reference balls is lost and gained in the complete process.

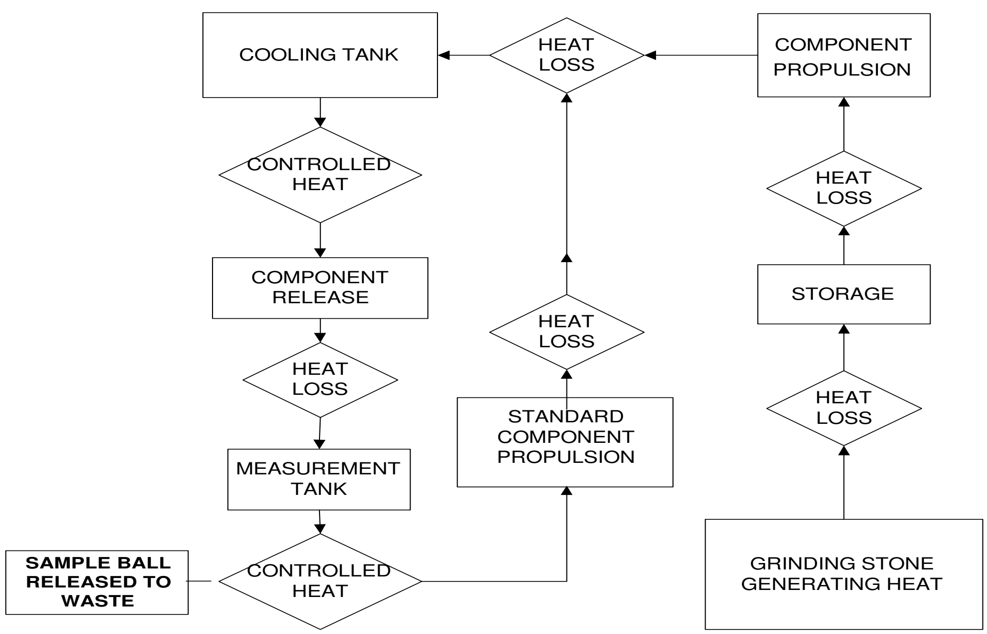


Figure 4-8 Heat gains and losses from grinding to measurement

4.3.6 Reference component separating unit

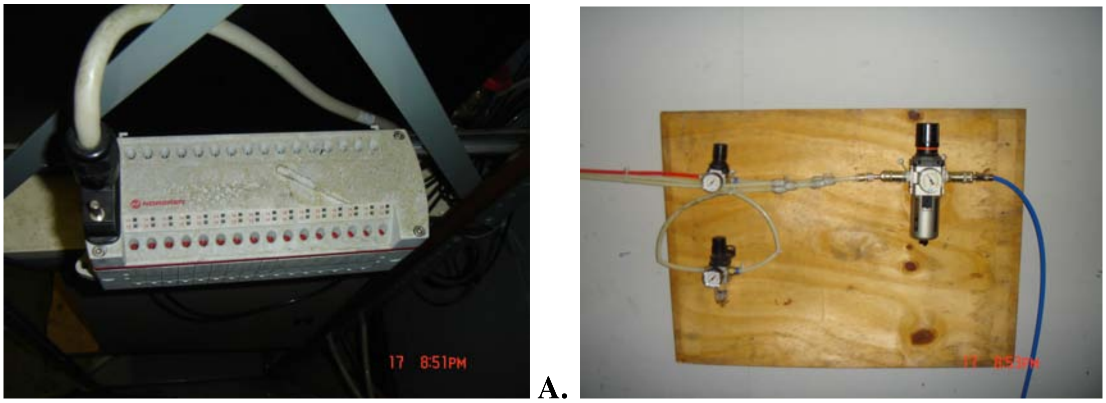
Before the measurement system measures the production samples, the upper and lower reference balls are measured to calibrate the measurement instrument. After they are measured they are directed down a pipe into a propulsion unit. As the reference ball enters the propulsion unit the entry valve closes to seal the propulsion chamber. They are then propelled by compressed air to a sorting unit (Figure 4.9).

Figure 4-9 Separating Unit

In this unit they are separated and are gravity fed into their individual pipes which are submerged in the temperature normalizing tank. The operation of the separating unit has been described in Section 3.4.1.

4.3.7 Mechanical components of the Plant

On the Pilot Plant there are several valves which open and close to allow the balls to be transferred through the system at different stages of the ball delivery process and reference ball re-circulation process. Each of these valves (See an example in Figure 4.7a) are operated via a 3/2 pneumatic valve, which are directly piped to one of the system regulator. When the automated system requires one of these valves to open, an output from the PLC switches on and send a 24V signal to a solenoid operated 3/2 valve and pipe valve opens. All of these valves operate at the same working pressure which is approximately 3 bar. The main air supply is piped directly through a larger 8 bar regulator and this feeds the two smaller system regulators (See Figure 4.10b).



A. B.

Figure 4-10 pneumatic valves on the Pilot Plant

The second system air regulator feeds a valve chest of 32 small 3/2 valves (See Figure 4.10a.)This valve chest is mainly used to supply air pressure of approximately 1.5 bar to the pin cylinders and smaller actuators on the Pilot Plant. These pin cylinders are used for the control of the ball injection system, ball delivery system and ball sorting system. This valve chest is wired to 32 outputs of the PLC via a 32 core cable. This cable is then simply plugged into the valve chest.

As the measurement tolerance is in the sub-micron range a filtration system was added to the Pilot Plant. This would decrease the likelihood of particles lodging between the ball and the measuring instrument at the point of measurement and offset the measured result. This filter is used to exclude particles above five microns in the coolant which may have entered the system from the atmosphere or with the samples. The filter was installed on the return circulating line from the measuring tank to the temperature normalizing tank (See Figure 4.11).

Figure 4-11 Coolant filter

Figure 4.12 shows the valve arrangement in the temperature normalizing unit. The pipe represented by the grey line is used for ball transport and the pipe represented by the black line is used for coolant recirculation.

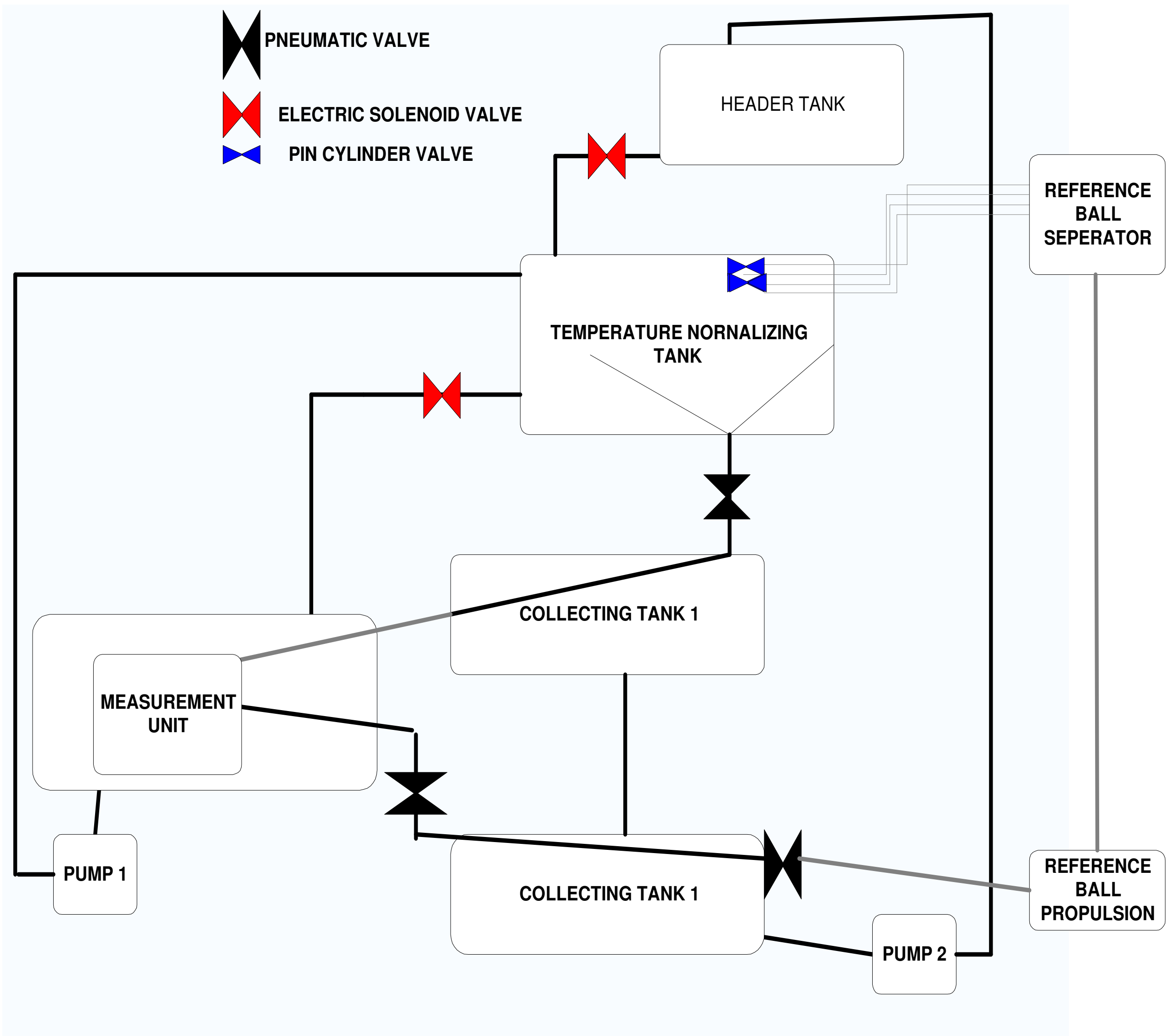


Figure 4-12 Pilot Plant valve system

System Incremental Improvement

During the testing phase of the project it became apparent that the high humidity level surrounding the piezo based measuring instrument was having an adverse effect on its functionality. When the coolant level was at the height of the measuring platform which is approximately 60mm below the measuring instrument, the measurement signal feedback ceased to exist. When the coolant was extracted from the measuring tank (thereby decreasing the humidity surrounding the instrument) the feedback functioned as normal. As the measuring instrument is so sensitive and also expensive the coolant piping was temporarily reconfigured to exclude the coolant from the measuring tank.

Before the reference and sample balls are released from the temperature normalizing tank they all have an equal temperature; from this point to their measurement they experience the same environmental exposure. Because of this and the level of accurate measurement the instrument delivers (1µm), it is currently neither an advantage nor a requirement for the ball to be submerged at the point of measurement. As the research is furthered with the measurement instrument and its accuracy increases to the targeted 0.1µm, the ball may be required to be submerged at the point of measurement and a means of protecting the piezo actuator will be found.

4.4 Ball Measurement

As previously stated the complete sampling and measurement system is divided into two Masters Projects, the first being the construction and control of a totally automated sampling system with means for machine parameter control feedback and the second concerned with the design, construction and control of the measuring instrument. This section of the chapter introduces the measuring instrument and summarises its design and construction. This information is taken for the MEng Thesis Pending 2008 [24], entitled "*Flexural hinge guided stage for sub-micron precision measurement",* by Madigan, D. and is included in this thesis to give the reader an understanding of the measuring instrument associated with the project.

Introduction

The measurement instrument is a flexural hinge, piezo-driven guided stage for sub-micron comparative measurement. The design features the use of precision solid flexures to transmit motion from a low voltage piezo stack to the measurement tip. This motion is used to determine height differences between standard and sample components. The product height dimension is subsequently computed from this for feedback control for the production process. The existing manual measurement accuracy achieved is 1µm. It is a comparative measurement process where both the production samples and the standard balls are held for a defined period in a controlled bath of temperature cooling fluid prior to measurement. In order to service a higher quality, higher value product, the company has targeted a measurement accuracy of 0.1µm.

4.4.1 Measuring instrument description and design

The measuring instrument consists of a primary flexural-hinge guided stage driven by a piezoelectric actuator. In-built into the primary stage is a secondary flexural-hinge guided stage, which again is driven by a piezoelectric actuator. The primary piezo actuator is used to drive the stage through long-travel positioning and the secondary acts as a touch sensor to detect contact between the measurement stage and the product. Figure 4.14 is a 3D CAD drawing of the stage mounted on a base with the ball delivery 'platform' in front of it.

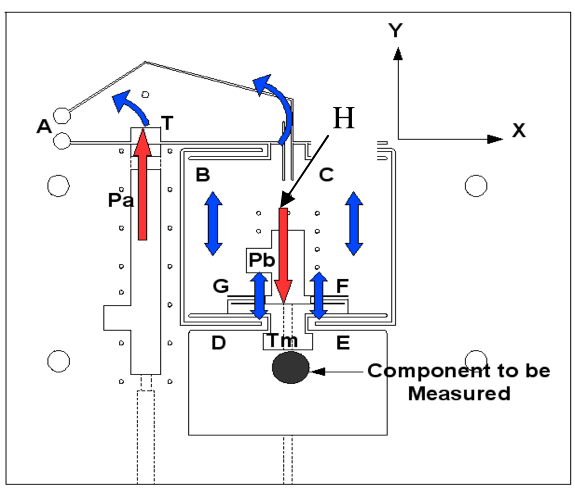


Figure 4-13 Stage Schematic

Fig.4.13 shows a schematic illustration of the measurement device. In this arrangement, a displacement at point *Ta* caused by movement of the primary piezoelectric actuator *Pa* is amplified through the lever mechanism. The displacement in the *y-direction* causes the entire stage to move in the upward direction, hence resulting in displacement amplification. The displacement at point *Ta* causes the lever to rotate. This rotation results in displacement offset in the x-direction. The transmission of this offset to the measurement point is largely eliminated by flexure *H* and by four leaf flexures B, C, D and E. Therefore the amplified displacement at point Tm will be linear and in the y-direction only. A sinusoidal voltage applied to the piezoelectric actuator Pb, will drive flexural hinges G and F and achieve a precise sinusoidal motion along the y-direction at the measurement point. Figure 4.14 shows a CAD drawing of the measuring unit.

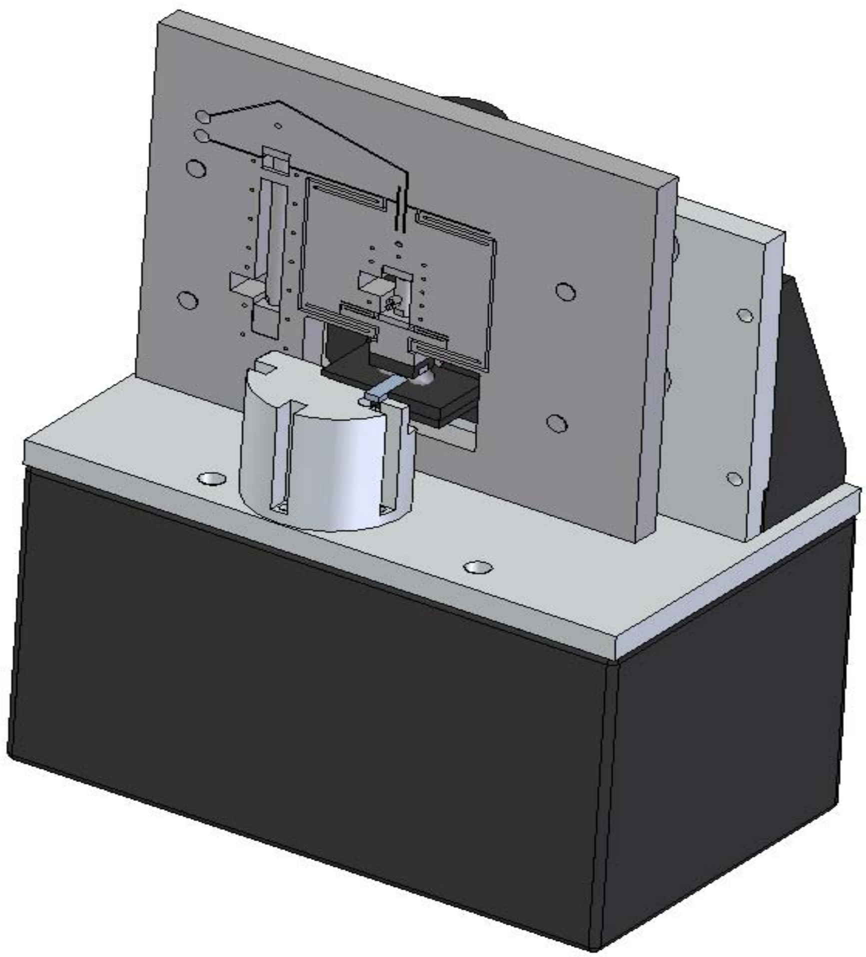


Figure 4-14 CAD drawing of the measuring unit

Measurement Principle [25]

The maximum and minimum reference balls of known height are used to calibrate the system. A continuous cycle of calibration followed by measurement is used. The expansion and contraction of the piezo actuators (See Figure 4.15) is tracked by means of two in-built strain gauges which can then (via the geometry of the flexural arrangement) be converted into ball height measurement (relative to the known diameters of the standard balls).

Figure 4-15 Piezo actuators *Pa* and *Pb*

Design

The design involves two different types of simple flexure arrangements. The first type is a cantilever with a simple notch hinge shown in Figure 4.16. This is used to amplify the displacement of the piezo actuator *Pa*.

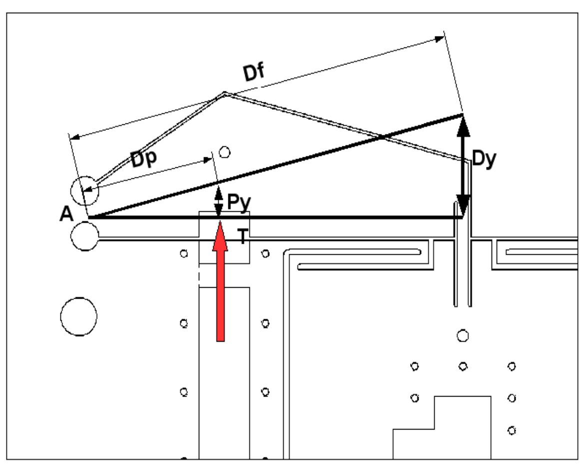


Figure 4-16 Notch Hinge [25]

The second type of flexure is a linear compound flexure hinge; this consists of four simple cantilever hinges, as shown in Figure 4.17. The objective of the linear compound flexure is to eliminate the displacement offset in the *x*-direction caused by the rotation about point *A*.

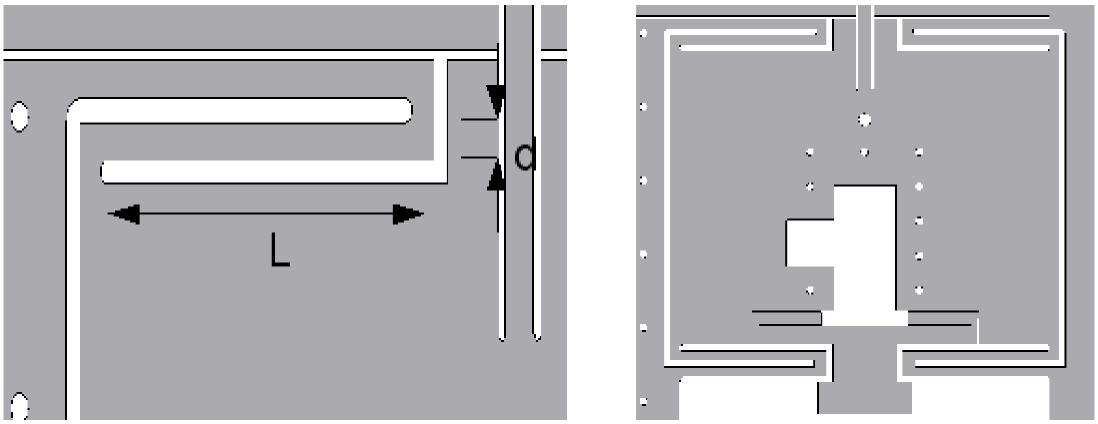


Figure 4-17 Flexural Hinge for Guided Motion

The range of motion of the stage will be restricted either by the stiffness of the flexural hinges through maximum force applied to the hinges, or the necessity not to exceed its elastic properties of the material. The stage is 20mm thick. The material used for the design is Aluminium 7075. This is a very high strength material used for highly stressed structural parts. This material has Young's modulus of 72 GPa, poisons ratio of 0.33, yield strength of 505MPa and fatigue strength of 160MPa, and a thermal expansion coefficient of 23.6×10^{-6}/K. Many other technologies exist for actuating and sensing to suit different application requirements. Flexure joints and piezoelectric actuators are the ones predominantly used for sub-micron measurement stages.

The embedded sphere location arrangement described in Chapter 3 as Prototype #2 was used in the ball locating system.

5 System control

Introduction

This chapter discusses in detail the automated control of the complete project. The overall control of the project is based on a hierarchical structure where a central controller commands several smaller controllers. Data, such as the required machines control parameters are sent to the smaller controllers and they can then return signals to represent the individual machine status (e.g. On/Off etc). This data is sent to and from the central controller via an ASI field bus network (See Chapter 6.3). The central controller is hard-wired to the Normalizing Plant to synchronize ball arrival, delivery and measurement. Also presented are the grinding machine wiring modifications which were required for synchronization with the central controller. Figure 5.1 shows a block diagram of the hierarchical control structure and the method by which the central controller communicates with grinding machine PLCs, measurement displays (M D), Normalizing Plant and Measuring System Unit (M.S.U).

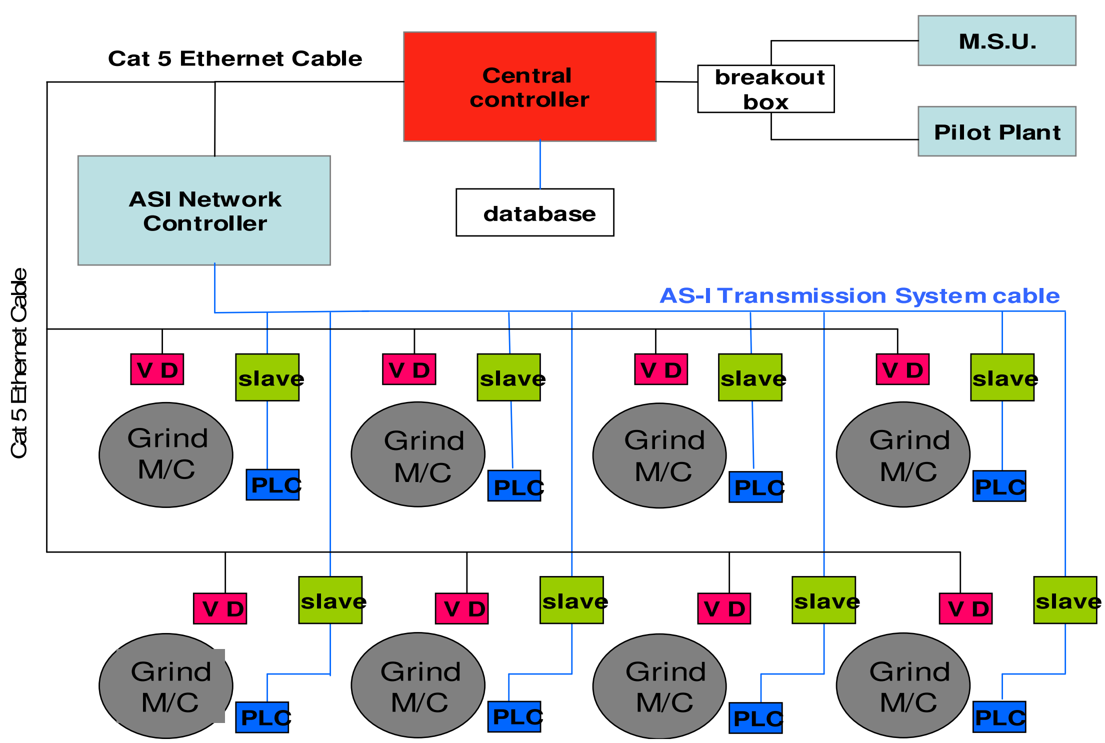


Figure 5-1 Control network block diagram.

5.1 The central controller

The central controller is a PC application developed in **LabVIEW** (short for **Lab**oratory **V**irtual **I**nstrumentation **E**ngineering **W**orkbench) which is a platform and development environment for a visual programming language from National Instruments. LabVIEW is commonly used for data acquisition, instrument control, and industrial automation on a variety of platforms including Microsoft Windows, UNIX, Linux, and Mac OS. The programming language used in LabVIEW, called G, is a dataflow programming language. Dataflow programming implements dataflow principles and architecture, and models a program, conceptually if not physically, as a directed graph of the data flowing between operations. Dataflow programming languages share some features of functional languages, and were generally developed in order to bring some functional concepts to a language more suitable for numeric processing. Execution is determined by the structure of a graphical block diagram (the LV-source code) on which the programmer connects different function-nodes by drawing wires. These wires propagate variables and any node can execute as soon as all its input data become available.

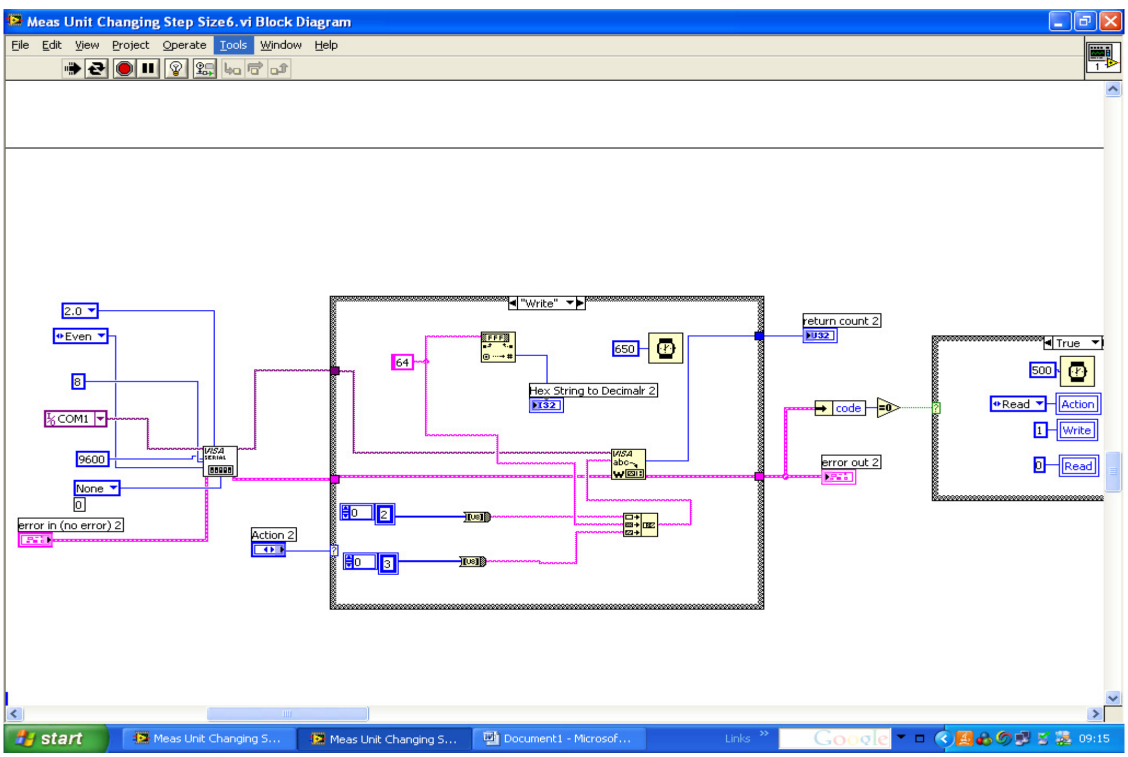


Figure 5-2 LabVIEW front panel for instructions to ASI controller

Figure 5.2 shows a screen shot of the block diagram developed to write instructions to the ASI controller. LabVIEW ties the creation of user interfaces (called front panels) into the development cycle. LabVIEW programs/subroutines are called virtual instruments (VIs). Each VI has three components: a block diagram, a front panel and a connector pane. The latter may represent the VI as a subVI in block diagrams of calling VIs. Controls and indicators on the front panel allow an operator to input data into or extract data from a running virtual instrument. Figure 5.3 shows a screen shot of a section of the project Front Panel at a development stage. This part of the front panel is dedicated to the communication with the ASI control network. The request for sample balls and the delivery of control parameters to the machines on the plant floor is controlled on this section of the front panel. The feedback regarding the operating status of the machines at the time of sampling is indicated at the top left of the screen shot.

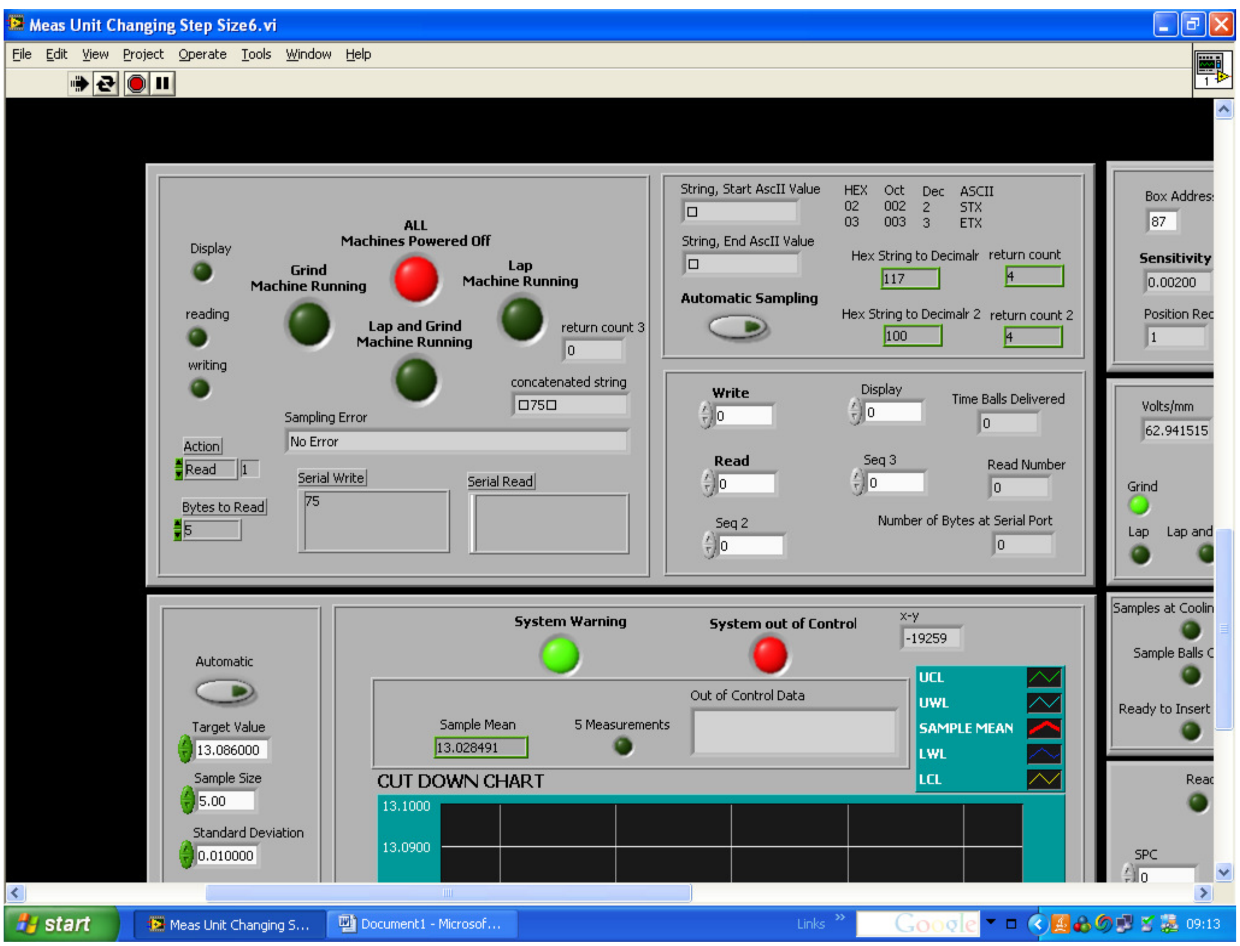


Figure 5-3 Screen Shot of a section of the project Front Panel

The central controller in this project communicates with external devices in two ways:

1. The PC serial port which links the LabVIEW application to the ASI network and the measurement Display units.
2. The Data Acquisition (DAQ) card and breakout box links the LabVIEW application to the pilot Plant PLC and the electronic circuitry of the measuring instrument.

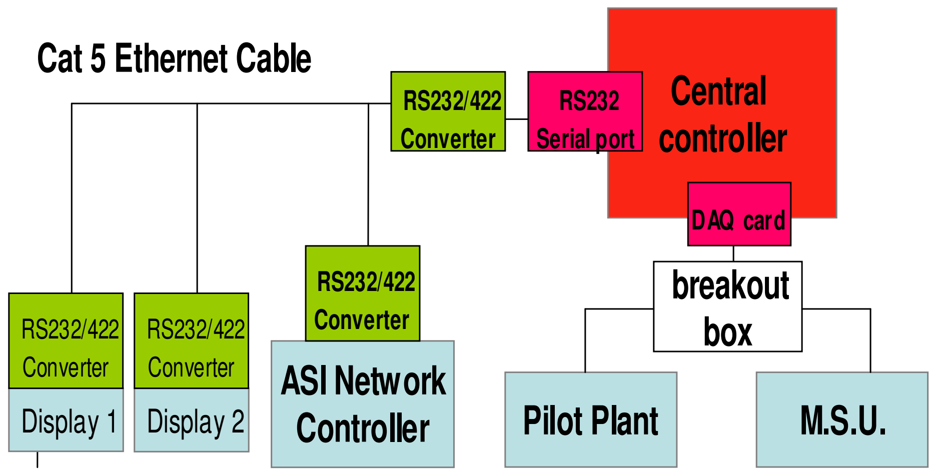


Figure 5-4 Central Controller Communication

Figure 5.4 shows the methods of communication to the central controller in block diagram form. The RS232 serial port is used to communicate with the ASI network controller. Because of the vibration and noisy environment the best location for the measurement station and central controller were situated over 200 meters from the grinding area. This considerable distance led to difficulty of signal transmission and signal converters were installed, as explained in the Automated networks Chapter.

The control signals to and from the Measuring system unit (M.S.U) and Pilot Plant PLC were received and transmitted via a Data Acquisition (DAQ) card which was installed to the central controller PC (See Figure 5.5a). DAQ hardware is what usually interfaces between the signal and a PC. It could be in the form of modules that can be connected to the computer's ports (parallel, serial, USB, etc...) or cards connected to slots (PCI, ISA) in the mother board. Usually the space on the back of a PCI card is too small for all the connections needed, so an external breakout box is required.

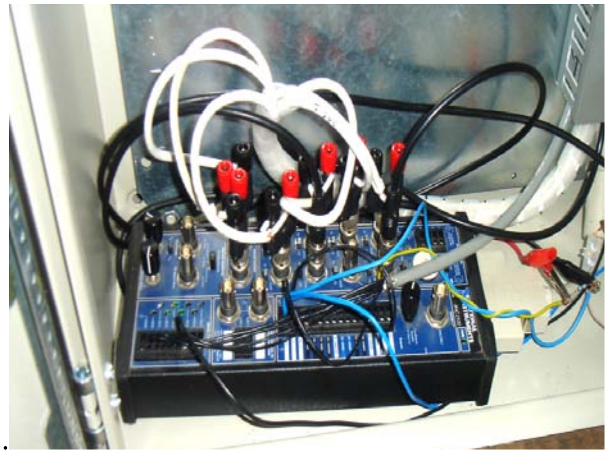
A.  **B**. 

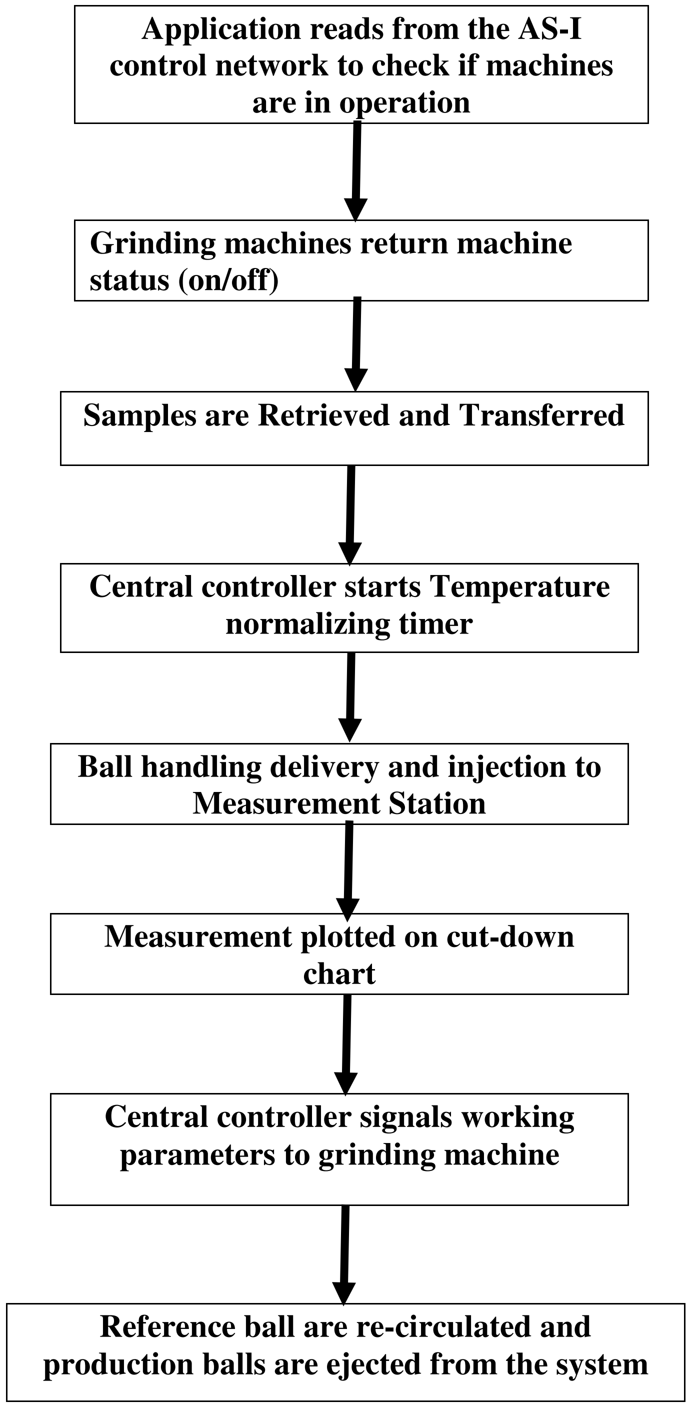
Figure 5-5 Data Acquisition card PCI 6024E and breakout box

Figure 5.5B shows a photograph of the breakout box used in this project. A breakout box is usually a box in which a compound electrical connector is separated or "broken out" into its component connectors. Compound connectors (which are often proprietary) are used where sufficient space for (or access to) connections is unavailable, such as on personal computer sound cards. If there are only a few connections, then a breakout cable (also octopus cable) may be used, as is common on smaller notebook computers.

In this project the physical property to be measured is the amount of stress on the strain gauge. When the ball is measured, the strain gauge on the secondary flexural hinge piezo actuator returns a signal to the central controller in the range of 0-10 volts. This indicates that the measuring device has touched the ball and the measurement is taken at this point from the primary flexural hinge piezo actuator (see Section 4.4.1).

In DAQ systems the feedback source is a transducer. The ability of a data acquisition system to measure different properties depends on the transducers to convert the physical properties into signals measurable by the data acquisition hardware. Transducers are synonymous with sensors in DAQ systems.

The transducer feedback is monitored from the Front Panel and the control system is supervised. The sequence of operations is as follows:



5.2 Grinding and lapping machine control.

This section of the chapter discusses the modified grinding and Lapping machine control systems and how they were altered to converse with the central controller via the ASI control network.

5.2.1 The Grinding Machine control system

As detailed later in Chapter 6, the selected grinding machine was fitted with a programmable logic controller (PLC) and an analogue to digital converter (A/D) to allow for automatic control of the machine and feedback to the Central Controller. The working parameters of the grinding machine are monitored by the PLC using a pressure transducer and a current transducer. The transducer signals are converted to a digital number by the A/D converter and stored in data registers on the PLC. When these digital numbers reach predetermined set points, the PLC controls the machine accordingly. Prior to this project the machine was hardwired and was operated manually using paper based feedback from a manual measurement station.

The pressure transducer is fitted to the hydraulic piping leading to the hydraulic ram which applies pressure to the grinding stone. The pressure transducer signal representing the machine working pressure is stored in a data register of the PLC. These numbers are then compared to upper and lower static control set points in the PLC program to maintain the required pressure designated by the central controller. The central controller can vary the machine pressure to five different pressures. When a particular machine pressure is chosen and delivered via the ASI network, one of five inputs on the PLC, labelled pressure1 to pressure5, is pulsed on, and consequently an internal relay is set on. Within the grinding process the working pressures range from 1000ps.i to 1400p.s.i. the analogue signal from the transducer is converted to a digital number between 0 and 255 which represents a range of grinding stone pressure between 0 and 600p.s.i. The A/D converter also has an offset function which enabled the digital signal to represent different pressure ranges. As the working pressures required are between 1000 and

1400p.s.i, the controllable pressure chosen is 900 to 1400p.s.i. Table 5.1 shows the analogue signals and their converted digital numbers.

Pressure number	Analogue signal, Pressure (p.s.i.)	A/D numerical value representing transducer signal.
	900 (62.1 bar)	0
5	1000 (68.9 bar)	45
3	1100 (75.8 bar)	90
1	1200 (82.7 bar)	135
2	1300 (89.6 bar)	180
4	1400 (96.5 bar)	225

Table 5-1 pressure transducer digital signals

As seen from Figure 5.6, only one of these internal relays can be on at one time. In this example, if pressure1 is on while pressure2-pressure5 is turned off, then internal relay M81 is set and M82-M85 are reset.

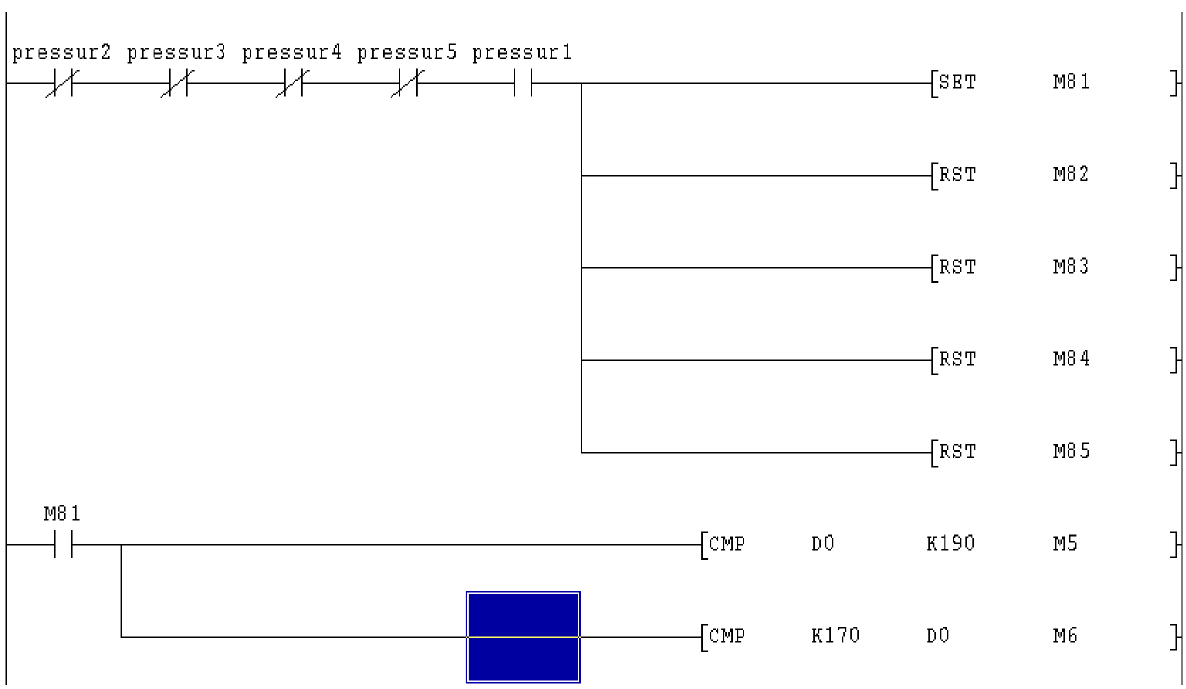


Figure 5-6 ladder logic for pressure transducer feedback

When M81 is turned on, it allows for the comparison to be made between the pressure transducer digital signals in data register D0 and the predetermined static set points which represent a specific pressure. In this case, when the transducer signal reaches the upper set point 190, internal relay M5 in turned on, which operates a PLC output to decrease the pressure slightly. As long as M81 is on, the digital signal will be maintained between 170 and 190 (approximately 180) which represent the desired working pressure for pressure 1. For each different pressure there is a section of ladder logic, similar to Figure 5.6, in the PLC program.

The machine is supplied by three phase current and the current transducer is fitted to one of these three phases. The main function of the current transducer is to aid an emergency stop system in the case of a potential grinding stone shatter. If a larger ball than the current batch size makes contact with the grinding stone the grinding pressure will increase rapidly and shatter the stone: as the pressure increases rapidly an immediate spike in the current is detected by the current transducer and is transmitted to the PLC. This is carried out using the same comparison method seen in Figure 5.6. When the current transducer signal stored in a data register reaches a high set point, which represents a spike in current and grinding pressure, M102 is turned on, which sets the emergency stop internal relay M8034. The PLC then shuts off all output and stops the machine before the grinding stone shatters. This part of the program is shows in Figure 5.7.

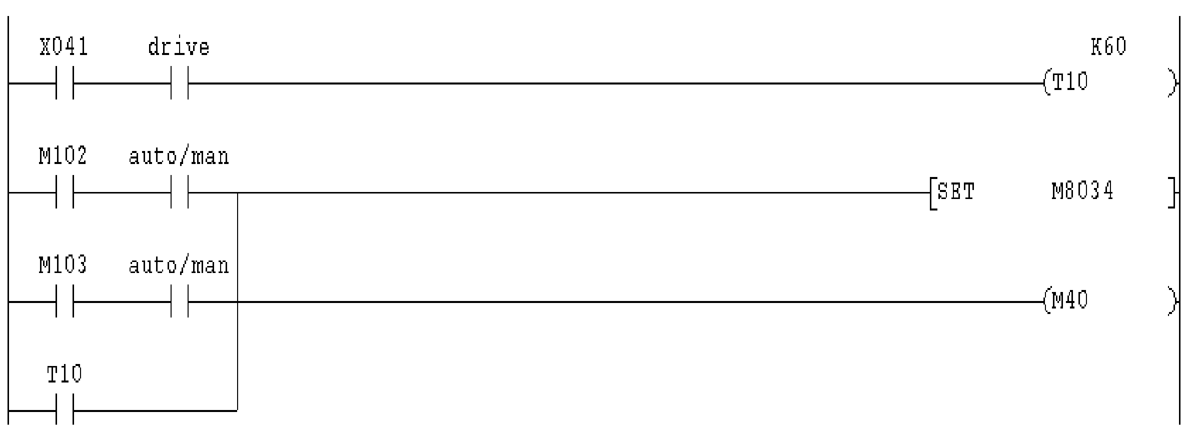


Figure 5-7 Emergency stop relay

On the side of the turn table, there a proximity sensor which controls the contactor for the turn table motor (see Figure 5.8).

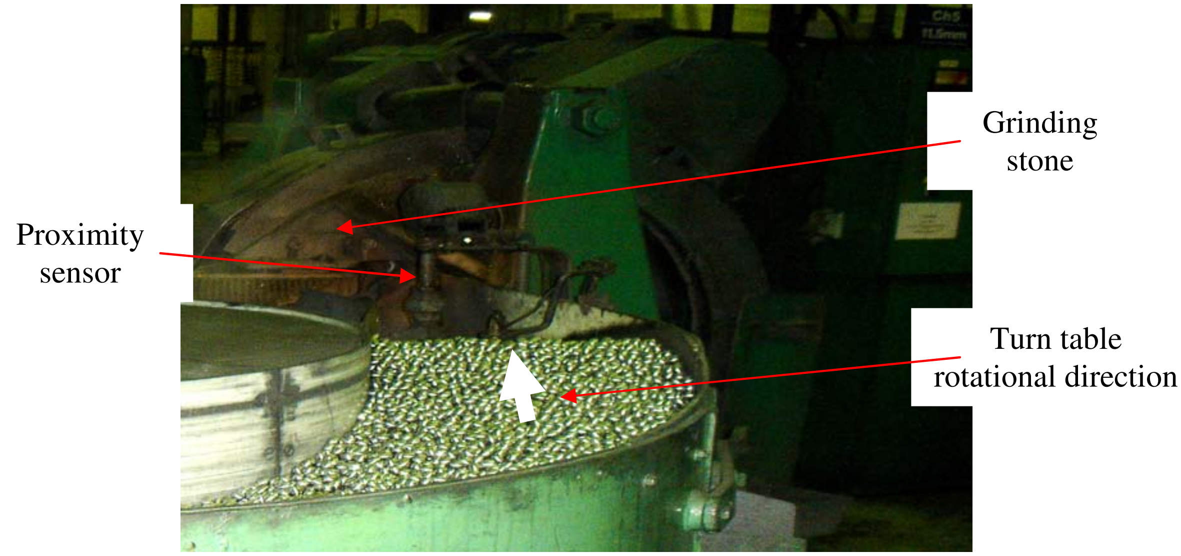


Figure 5-8 Approach Plate sensor

When the balls back-up on entry to the turn table, the balls hit the proximity sensor and the table stops rotating and allows the build-up of balls to enter the grinding stone. This ensures that the grinding stone has balls in its grooves at all time and they do not back-up over the side of the table during the grind process. If the balls stop at the entry to the grinding stone for any reason while the stone is still turning, the stone will push towards the plate and be damaged. This may happen if the drive card of the turn table malfunctions or stops. As an extra precaution the same signal from that proximity switch is wired to input X41 on the PLC. If X41 turns on while the machine in drive mode, timer T10 starts. The proximity sensor is turning on and off, on a continuous basis approximately every three or four seconds to control feeding of the balls to the grinding stone, therefore T10 should not complete a 10 second count. If the turn table does not work the proximity sensor will stay on continuously. As shows in Figure 5.7, if X41 remains high, T10 will complete a 10 seconds count and the normally open contact T10 will close to activated the emergency stop relay M8034.

PLC connection to the ASI slave

As described later in Chapter 6, the AS-I slaves used in this project (Fig 5.1) have two input and two outputs each. For this machine, three slaves are needed to cater for the six inputs required (five different pressure signals and the ball retrieve signal). The slave inputs are wired to the inputs of the PLC which control the inputs (pressure1 – pressure5) shown in Figure 5.6. The slave outputs are wired to the outputs of the PLC. Only two of the slave outputs are required with this control system. As shown in Figure 5.9, when the machine is in drive mode the normally open drive contact closes and turns output Y41 high. This sends a signal to the central controller via the ASI control network which represents "machine on". When the machine is not in drive mode, the normally closed contact opens and output Y42 goes high to signal "machine off".

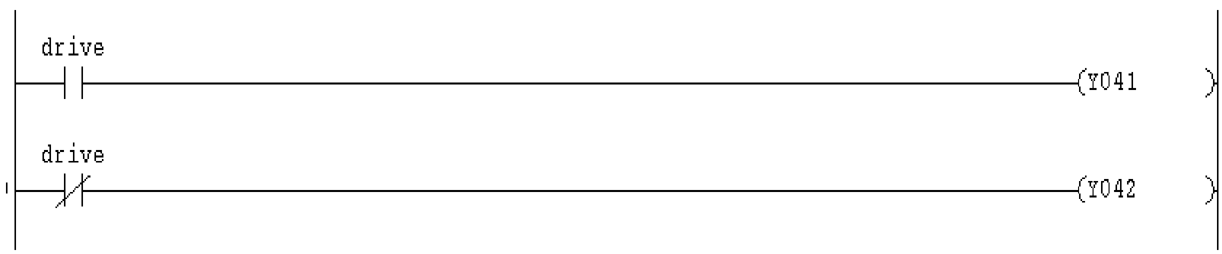


Figure 5-9 slave output control

5.2.2 The Lapping Machine control system

The existing method of machine control was not altered for the lapping machine selected for the automated measuring system. Reasons for this are explained in detail in Section 6.2 of Chapter 6. Even though the existing controls were not altered, a control system for the retrieval and propulsion of the sample balls had to be put in place (Explained in Section 5.3 of this chapter).

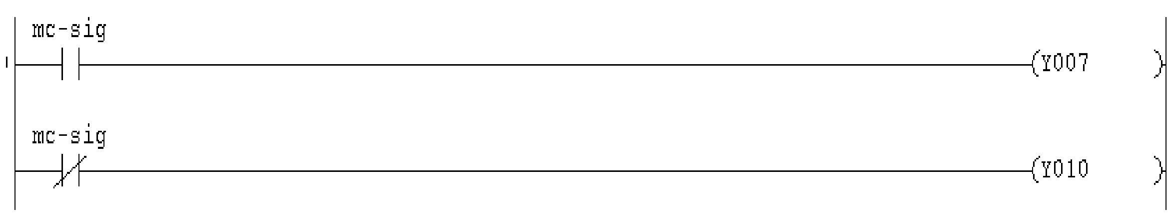


Figure 5-10 machine status signal

The signal representing the machine status was salvaged from the inverter which controls the rotational speed of the grinding stone. When the stone is turning a spare normally open contact closes in the inverter circuit and this is used to switch an input on the PLC. This input, titled "mc-sig" in the PLC program controlled two PLC outputs Y7 and Y10 (see Figure 5.10), which signals the machine status to the AS-I slave. The complete program for the grinding machine control can be seen in the appendix M.

5.3 Component Handling Control

This section of the Chapter discusses the control of the complete component handling system. There are three different areas related to component handling in this project. These are component retrieval, propulsion and delivery. This covers the complete physical transfer from retrieving the sample from the machine turn table to the ejection of the ball from the measuring instrument

5.3.1 Component Retrieval Control

The sample consists of five balls taken from the batch at predetermined intervals during the grinding process. The control of the pick and place unit (described in detail in Chapter 3) was carried out by the grinding machine PLC: compressed air was used to carry out the mechanical functions of the pick and place unit. An external control cabinet was constructed to contain the pneumatics regulators, stop valves and switch gear for the retrieval and propulsion systems. This cabinet was then linked to the outputs of the grinding machine PLC via a single multi-core cable.

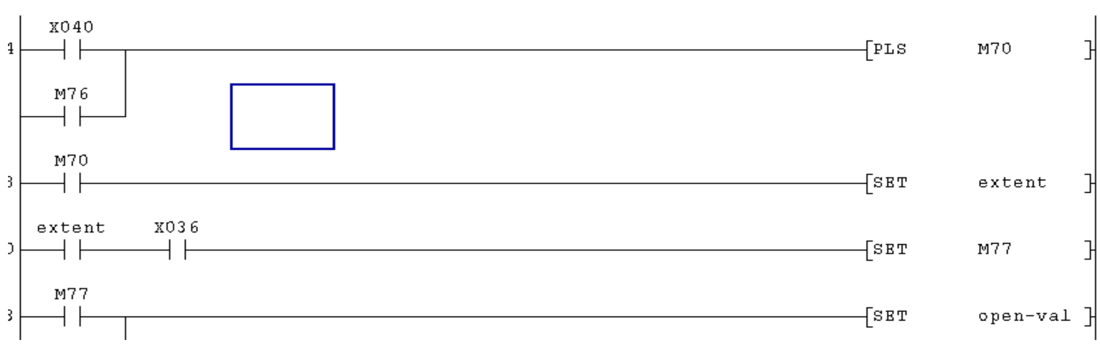
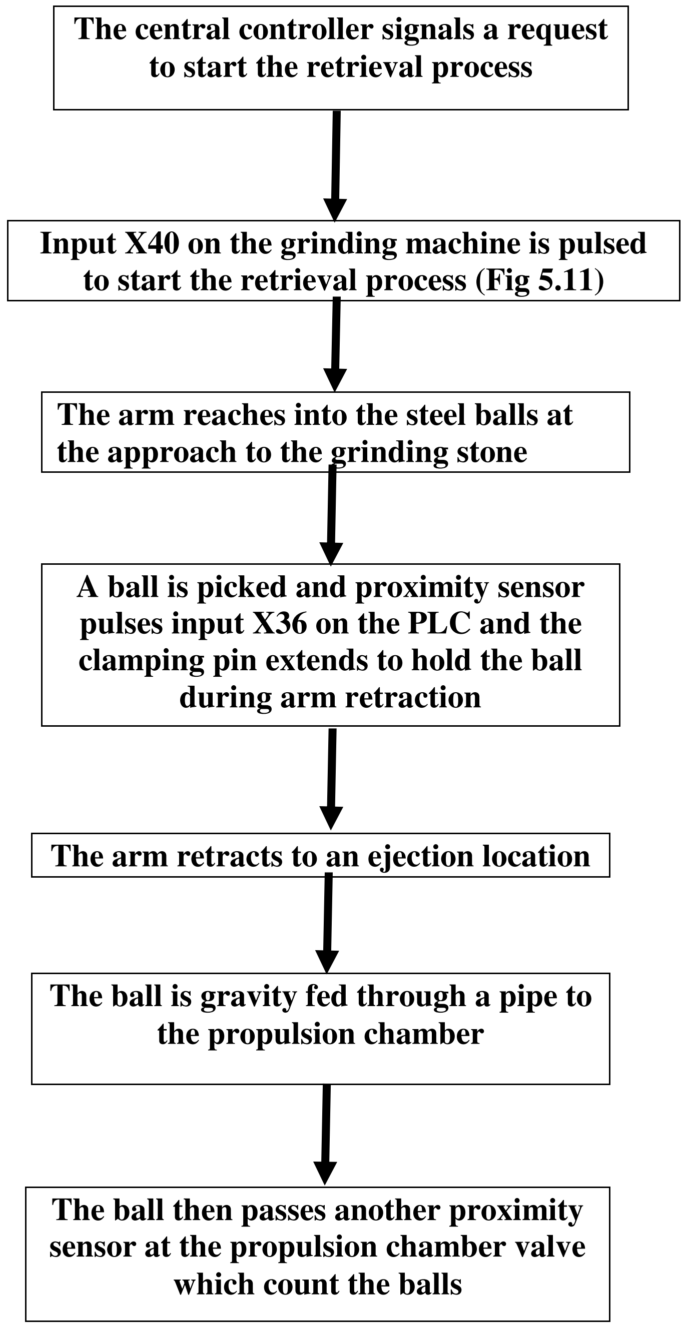


Figure 5-11 beginning of retrieval sequence

The retrieval control sequence of operations for a complete retrieval process is as follows:



When the above sequence loops five times, the normally open contact C20 closes which sets the output Y34 to close the propulsion chamber valve (see Figure 5.12) and resets the retrieval pick and place arm until the next signal to sample.

Figure 5-12 end of retrieval sequence

5.3.2 Component Propulsion Control

The propulsion system construction details are outlined in Chapter 3. Like the retrieval system, the propulsion system is also operated by compress air and controlled by the grinding machine PLC. When the signal is given, a 10mm internal diameter 3/2 valve is opened by an electrical solenoid and the sample is propelled by compressed air through a 20mm pipe to the temperature normalizing station.

The controlling program is a continuation of the retrieval program using the timer T73. Its sequence of operations had three steps:

1. Timer T73 is activated by timer T72 which controlled the last operation in the retrieval process. T73 is set for 1 second. At this point the five ball sample is sitting in the propulsion chamber.

2. After one second elapses, the normally open contact T73 closes and sets the output which signals ball propulsion. Simultaneously, timer T74 begins a fourteen second timing sequence, which is sufficient time to propel the 13mm balls from the machine to the temperature normalizing location.

3. After fourteen seconds elapses the normally open contact T74 closes and resets the ball propulsion signal. At this stage the sample is at the temperature normalizing station and the propulsion system is ready for the next sample to arrive from the retrieval system. Figure 5.13 shows a section of the PLC program for the propulsion system control.

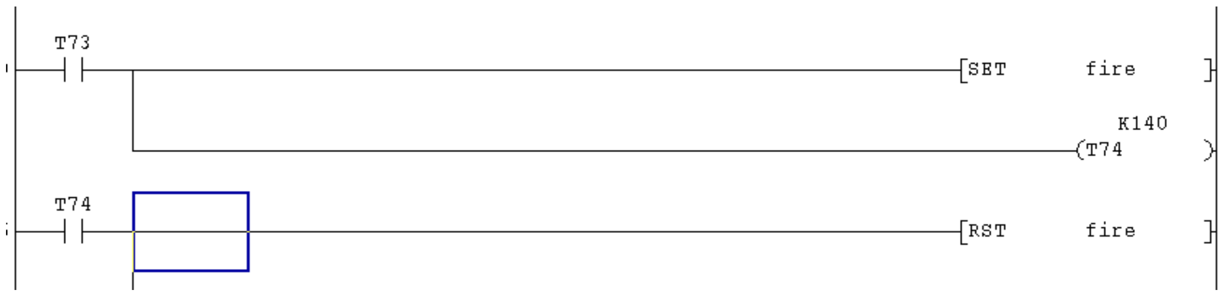


Figure 5-13 propulsion system programming sequence

5.3.3 Component Injection Control

The injection control system is in three stages. These are detailed in Section 5.4 of this chapter as they are under the control of the Temperature Normalizing PLC.

Stage1Release of the balls form the temperature normalizing tank

Stage2. The ball injection to the measuring instrument

Stage3. The re-circulation of the calibration balls to the temperature normalizing tank.

After stage 1 of the process is complete there are two calibration and five sample balls waiting in the injection system. The command to inject a ball is given from the central controller to an input on the Temperature Normalizing PLC. At this point the PLC automatically carries out a series of steps to synchronise and control the operation of three pin cylinders and one ball blowing device to inject each of the balls to the measurement instrument. This sequence is as follows:

- The central controller signals the PLC when the measuring instrument is ready.
- The normally open contact labelled “insert” closes and sets internal relays M1&2.

Figure 5-14 ball injection program

- M1 then retracts the first holding pin cylinder 0.2 seconds before the ball pusher and the second holding pin cylinder extend (see Figure 5.14). This combination of operations leaves the first ball held behind the second holding cylinder.

- After one second; cylinder 2 retracts to gravity feed the ball into the measuring platform, the pusher cylinder retracts and the cylinder 1 extends. The next ball is now located behind cylinder 1 and in front of the retracted pusher cylinder.

- The first ball is now measured by the measuring instrument (explained in Section 4.4.1 of Chapter 4).

- After the first ball is measured the central controller automatically signals the injection of the next ball to the measuring platform.

- M2 controls the air blower device which ejects the balls from the measuring platform. This operates every time the central controller signals the PLC to clear the platform before the next ball insertion (see Figure 5.14 and 5.15).

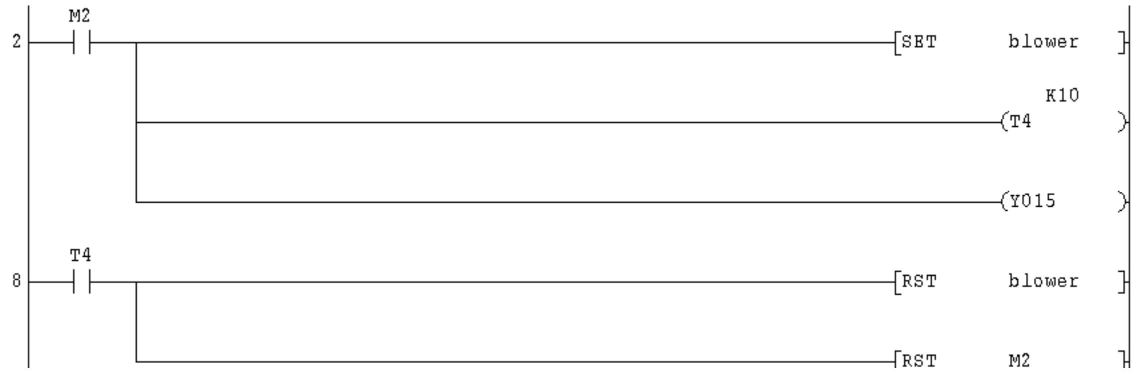


Figure 5-15 ball removal program

- The first two balls to be measured are upper and lower calibration balls which calibrate the measuring instrument. They five ball sample is then measured one at a time and the result is saved to file. After the seven balls have been measured the central controller wait for a signal from the Temperature Normalizing Plant which indicates the arrival of the next sample to the injection system. The process then begins again.

5.4 Temperature Normalizing Plant control

This section of the chapter discusses all aspects of the projects that are controlled by the Plant PLC. Also outlined is the synchronized control of the Pilot Plant with the central controller.

5.4.1 Synchronizing Pilot Plant with Measurement Instrument

As the measuring instrument with its ball injection system is controlled directly by the central controller and the temperature normalization operation is controlled by the Temperature Normalizing Plant PLC, a means of synchronization is required for the measuring system to operate effectively.

There are four main signals to and from the central controller and Temperature Normalizing Plant Plc to maintain synchronization:

1. As the samples arrive their proximity sensors signal the central controller. The central controller then signals the Temperature Normalizing Plant PLC to indicate what machines are involved in the particular measurement process.

2. After the balls have arrived at the temperature normalizing tank and have been cooled for thirty seconds the central controller signals the Temperature Normalizing Plant PLC to begin the delivery of the sample and the associated calibration balls. This is described in the next Section 6.4.2.

3. When the sample arrives at the injection system, the Temperature Normalizing Plant PLC signals the central controller to indicate the arrival and that the ball injection and measurement cycle may commence.

4. As each ball is being measured the Temperature Normalizing Plant receives a pulse which is stored in a counter of the PLC program. This is to signal the release of the next sample when the first sample measurement has been completed.

5.4.2 Ball Delivery Control

When the samples arrive in to the temperature normalizing tank as explained in section 3.3.2 they sit in their own individual pipes for thirty second duration (to equalize the temperature between the sample and the calibration ball). Both the calibration balls and the samples are held by a pin cylinder located at the end of each pipe. These pin cylinders are controller by the Temperature Normalizing Plant PLC which coordinates the sample release process. When the thirty seconds elapses the ball delivery process begins. The measuring system expects the balls to arrive in formation. This formation is; upper calibration ball first and then lower calibration ball, with the sample to follow. To ensure the correct arrival formation at the measuring system, a delay is installed between the release of each component. The ball release and delivery operation is sequenced as follows:

- The central controller signals to the PLC that samples are available for measurement.
- The central controller signals the beginning of the delivery process with the release of the first available sample. With this pulse an internal relay is set and the upper calibration pipe pin cylinder is retracted for a half second to release the upper calibration ball (see control logic in Figure 5.16).

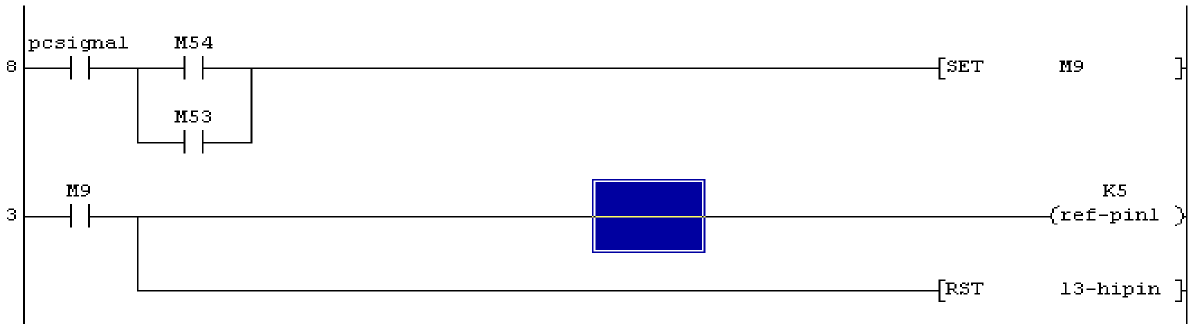


Figure 5-16 beginning of ball release process

- After another one second delay, the same operation happens for the lower calibration ball. Both the upper and lower calibration balls have now been funnelled to a pipe and are in formation at the bottom of the temperature normalizing tank.
- The first sample pin cylinder is then retracted to release a five ball sample which follows the path of the calibration balls.
- The main release valve is then opened for one second to release the seven ball formation. They gravity feed from the temperature normalizing tank through a copper pipe and enter to the ball injection system.
- As the balls are being measured the PLC receives a pulse for each of the balls. When the seventh pulse is received the next available sample is released. This process continues until all available samples have been measured.

5.4.3 Reference Ball Re-circulation Control

When the balls are measured, the calibration balls need to be re circulated back to their cooling pipes in the temperature normalizing tank as outlined in Section 3.4.1. The balls are gravity fed from the cooling pipes to the measurement unit; therefore, to recycle the calibration balls another propulsion system was installed. An automated sorting unit was also fabricated to divide the calibration balls to their correct cooling pipes. The sequence of operations for the calibration ball re-circulation is as follows:

- The Temperature Normalizing Plant PLC receives a pulse when each ball is measured and ejected from the measurement platform. The PLC will receive seven pulses throughout the first sample measurement. The first two pulses received indicate that the calibration balls have been ejected and next five represent the sample.

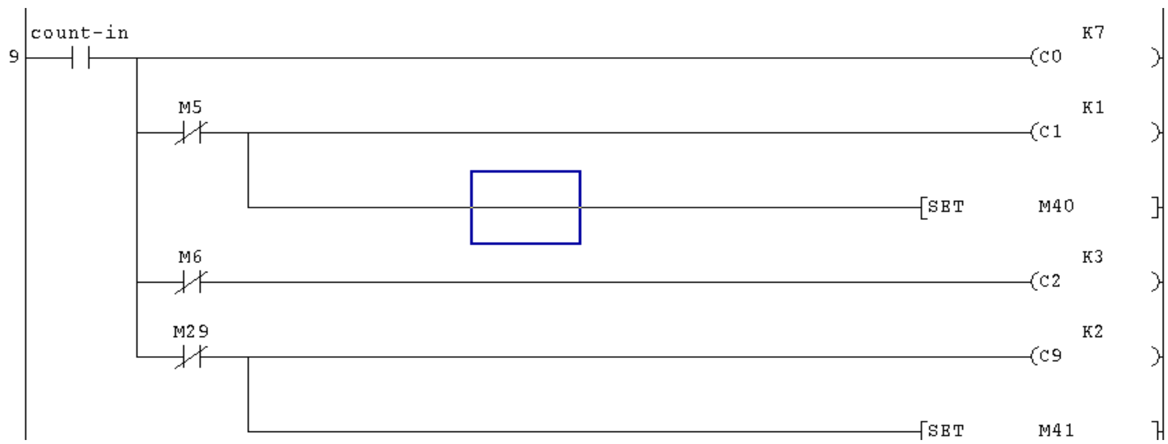


Figure 5-17 ladder logic for measurement ball count

- As shown in Figure 5.17 each pulse temporarily closes the normally open contact labelled “count in”. The first pulse completes the C1 counter which set M5 to allow no more pulses to be counted on C1. It also commands a normally extended cylinder to retract to guide the first and second measured ball (calibration balls) to the recycle valve in the measuring tank. On the third pulse counter C2 completes and the guide cylinder extends to guide the other five balls to the exit valve in the measurement tank where they are momentarily held before exiting the temperature normalizing tank. As the guide cylinder lifts to guide the calibration balls, a signal is simultaneously sent to the recycle valve and the entry valve to the propulsion chamber to open for two and three seconds respectively.

- When the entry valve closes, the signals to propel the ball and extent the assigned pin cylinder in the dividing unit are outputted. This is done through the sequencing of internal relays. For example, the combination of setting M40 and M54 high extends the pin cylinder labelled “sortpin1” (see Figure 5.18).

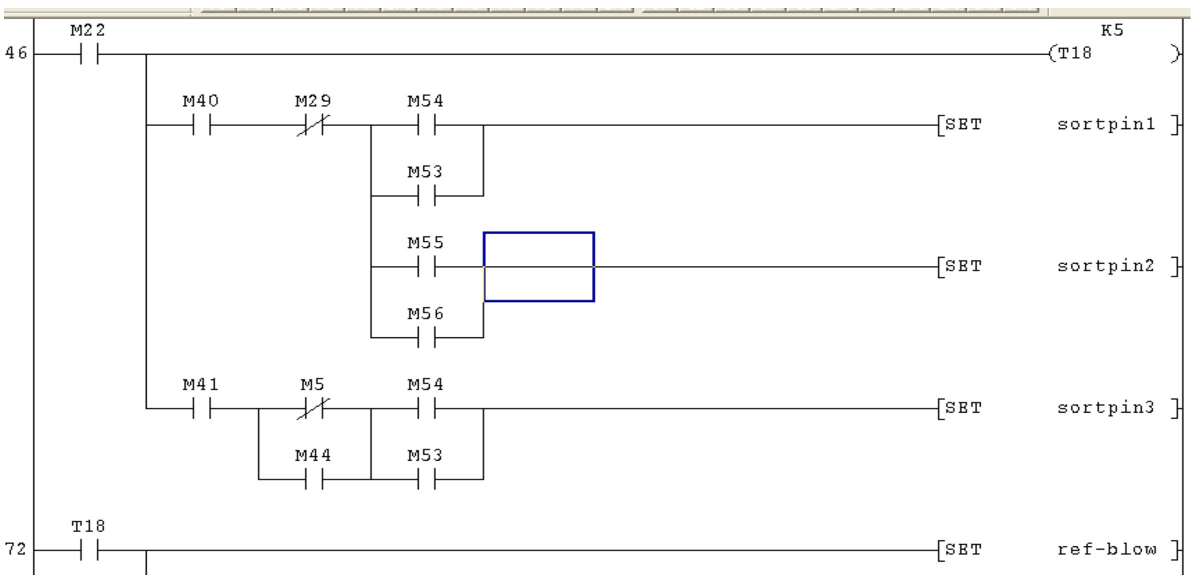


Figure 5-18 ladder logic for sorting unit control

- The ball is now located held by the extended pin cylinder at a specific location on the sorting unit floor. The floor is then lifted to allow the balls to fall from the sorting unit to a specific cooling pipe. This complete process is the repeated for the second calibration ball. The relocating duration is approximately four seconds.

5.4.4 Temperature Normalizing control

Other than the synchronized control of the ball delivery and re-circulation system, the Temperature Normalizing Plant PLC controls:

1. The temperature normalizing control of the coolant.
2. The circulation of the coolant between the measurement tank and temperature normalizing tank.

3. The basic control functions (start, stop, warning lights).

The system is controlled by started by a push button which operates the internal relay M3. When M3 is set the circulating pump is turned on and the main solenoid diaphragm valve is open to allow circulation between the measurement tank and temperature normalizing tank. When M3 in set, the start light illuminates to indicate that the Temperature Normalizing Plant is in operation.

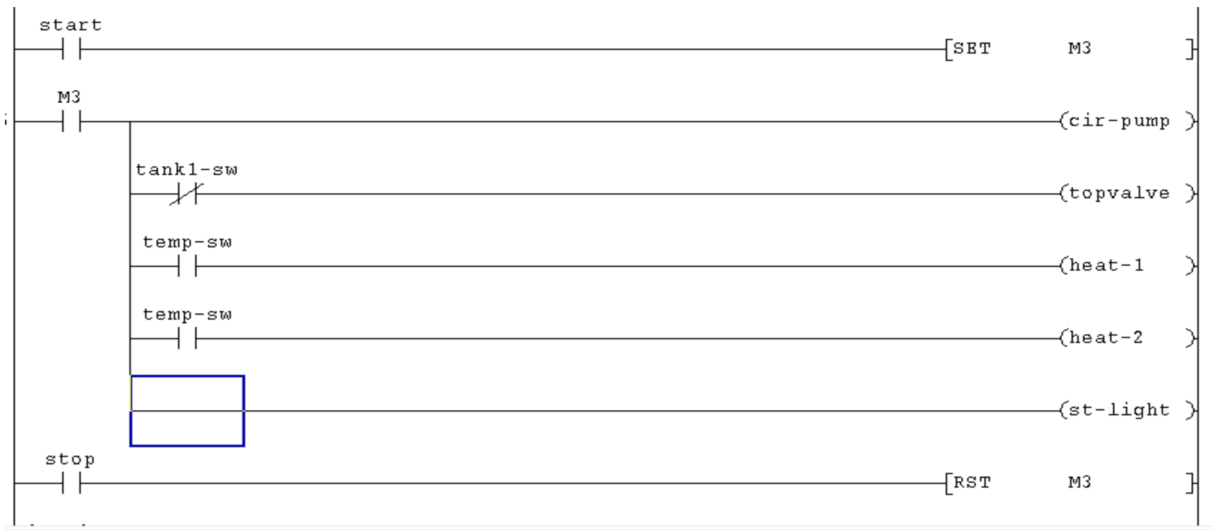


Figure 5-19 Pilot Plant basic controls

The installed temperature control unit uses the PLC to control the switching of current to the heating elements. If the temperature of the coolant drops below the set point, the temperature control unit switches a 24 volt signal to the input X2 on the PLC which closes the normally open contact labelled "temp-sw". If M3 is set and "temp-sw" is closed, heating elements 1&2 are switched on until the temperature rises to the set point again which switches off input X2 on the power to the heating elements. This logic control is illustrated in Figure 5.19.

The re-circulation of coolant from the collections tanks is carried out when the float switch in the lower collecting tank closes. This signals input X3 which closes the normally open contact labelled "drai-sw" and sets the output controlling the drainage pump for thirty seconds. The ladder logic for this operation can be seen in Figure 5.20.

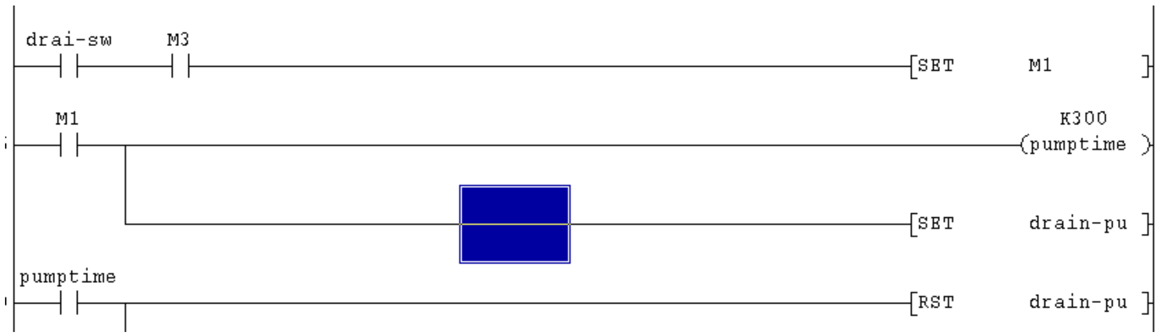


Figure 5-20 drain pump control logic

When the coolant in the temperature normalizing tank drops the installed float switch opens and the normally closed contact labelled “tank1-sw” opens. The output controlling the exit valve on the header tank opens and tops up the coolant in the temperature normalizing tank. The controlling ladder logic for this function can be seen in Figure 5.19. There is also a low level float switch in the header tank. When this float switch opens an indicator light illuminates to indicate a requirement for coolant to be added to the system.

5.5 SPC and Network control

This section of the Chapter discusses the control of the complete network and how the data is formatted at both the central controller and the AS-I side of the network. Also outlined is the SPC system which interprets the measurements taken and sends the appropriate feedback to the grinding machines.

5.5.1 Serial port read/Write

The serial read and write functions are part of the central controller LabVIEW application and is controlled and monitored from the front panel screen. The read function is used to identify the status of the machines, and the write function is used to instruct the machine controllers. A screen shot of this front panel is shown in Figure 5.21. The controlling program for this front panel in written in block diagram form.

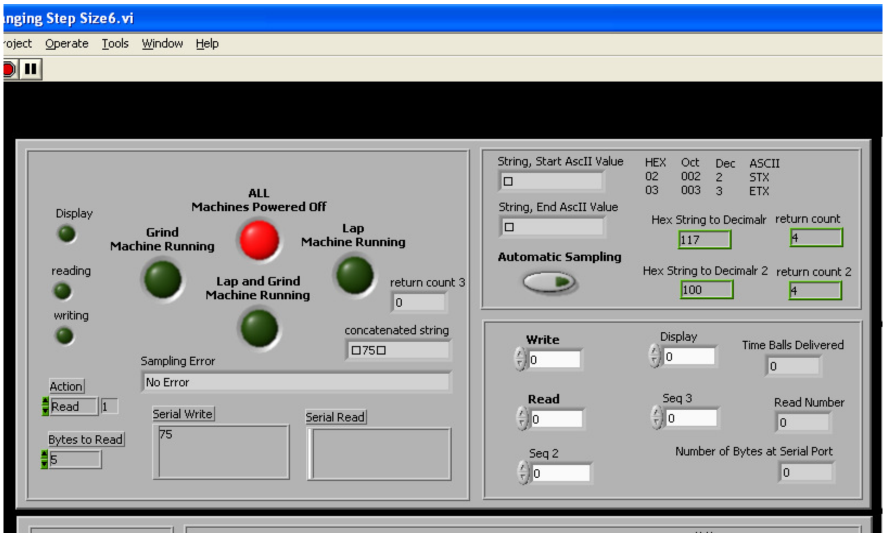


Figure 5-21 screen shot of the Front panel control for Serial read/right.

When the write function is enabled, the decimal number in the Serial Write dialogue box is converted to ASCII and these characters are placed between an ASCII start bit and stop bit to form a string. These start and stop bits are displayed on the top right corner of Figure 5.21. This string is then sent to the serial port. The start and stop bits are used so that the external devices (AS-I network controller) can identify the string.

5.5.2 Serial port read/Write and ASI Network control

BFM #0: Communication format

Bit	Description	0	1	Initial value
b0	Data length	7 bit	8 bit	1 : 8 bit
b1 b2	Parity	(00) : None (01) : Odd (11) : Even		(11) : Even
b3	Stop bit	1 bit	2 bit	0 : 1 bit
b4 b5 b6 b7	Baud rate (bps)	(0011) : 300 (0100) : 600 (0101) : 1200 (0110) : 2400 (0111) : 4800 (1000) : 9600 (1001) : 19200		(1000) : 9600 bps
b8 b9	Control line	(00) : Not used (01) : Standard RS-232C (11) : RS-232C interlink connection mode		(00) : Not used
b10 b11	Addition of CR and LF	(00) : Not added (01) : CR only (11) : CR and LF		(00) : Not added
b12 b13	Availability of check sum and ASCII/HEX conversion	(00) : Not available (01) : ASCII/HEX conversion available (10) : Check sum available (11) : Check sum available, ASCII/HEX conversion available		(00) : Not available
b14	Send/receive buffer data length	16 bit	8 bit	0 : 16 bit
b15	Undefined (disabled)			0: Undefined

Figure 5-22 communication Format table [26]

The RS232 interface block (FX2n-232if) is connected to the PLC to realise full duplex serial data communication between the AS-I PLC and the RS232 interface on the central controller PC. The RS232C interface block Rs232if exchanges data with the Pc via the buffer memories BFMs (16 bit RAM memories) in the RS232if. Send/Receive (read/write) data is received and sent through the FROM/TO instruction in the Ladder logic program. The communication format is first outlined by selecting the specific details of the format required from the table in Figure 5.22.

Depending on the selected format, a 16 bit binary number is generated and converted to Hexadecimal. Using the table in Figure 5.22, an example of a specifically selected format with the representing binary number and its Hexadecimal equivalent is shown in Figure 5.23.

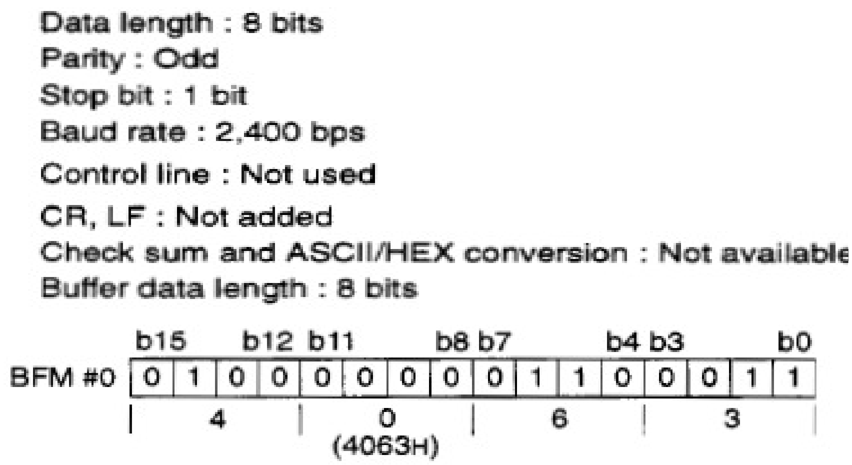


Figure 5-23 example of the a specifically selected format [26]

This Hexadecimal number (e.g. 4063h) should be initially transferred using the "TO" instruction before any of the BFMs are turned on. An example of this instruction is shown in Figure 6.24

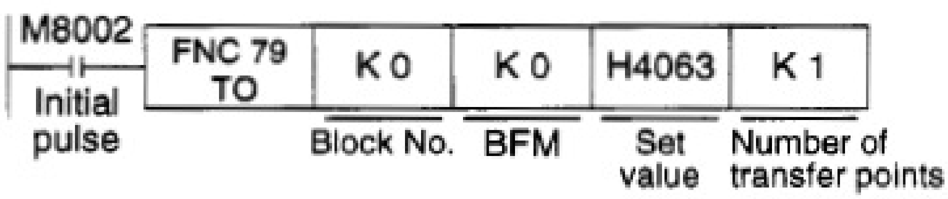


Figure 5-24 block diagram of the "TO" function segments [26]

Each of the slave inputs and outputs are controlled by the internal relays in the PLC. These are linked through part of the AS-I Master initializing ladder logic using a "TO" and "FROM" instruction (see Figure 5.25). This instruction links the control of the slave inputs to internal relays to M200 to M299 and the control of the slave output to internal relays M300 to M399.

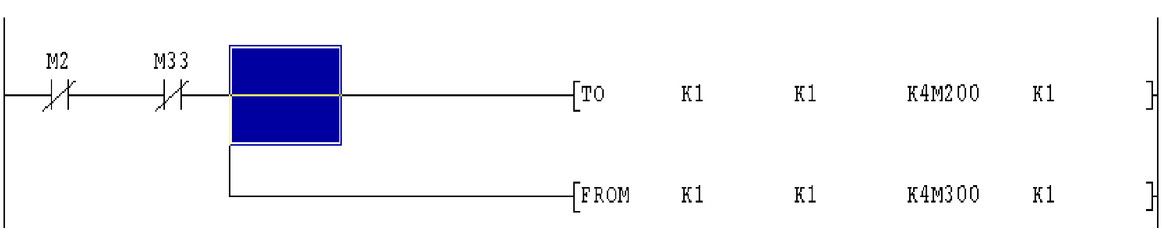


Figure 5-25 Initializing AS-I ladder logic

When the central controller sends a command to the AS-I controller, it arrives in ASCII form. It is then converted to decimal and placed in data register D301 by request, using the "FROM" instruction (Figure 5.26). Using the compare instruction "CMP" an internal relay is turned on to pulse a signal to one of the slave inputs within the AS-I network.

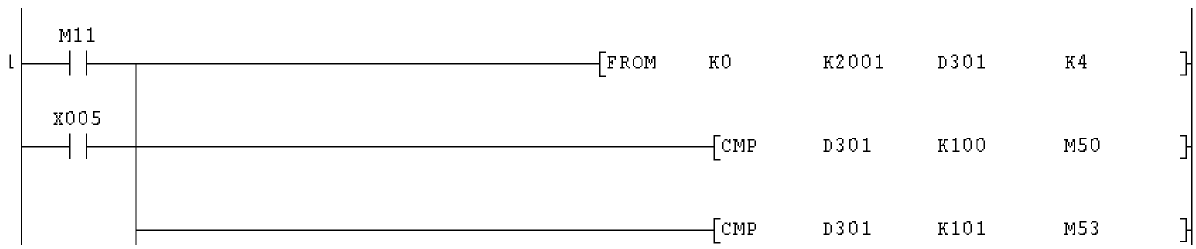


Figure 5-26 "FROM" instruction

The functionality of the compare instruction in explained in the following example [27]: Using the compare instruction "cmp D0 K10 M1", each time the instruction is executed, the logic states of the internal relay M1, M2 and M3 will indicate the result as follows:

M1 on if D0 > 10

M2 on if D0 = 10

M3 on if D0 < 10

Therefore, if the instruction number stored in D301 is equal to the static number to which it is being compared, M51 will be switched on. Using the first compare instruction in Figure 5.26 as an example; if the number in D301 is equal to 100, M51 is turned on. M51 is then used to trigger internal relay M200 which turns on the first slave input.

In order for the central controller to receive data from the AS-I controller it must send a command to read. When this command is sent internal relay M150 is turned on which pulses the read relay M1. The "TO" instruction then sends data, via the RS232 interface module, from a data register in the PLC to the central controller. Each separate message to the central controller has its own "TO" instruction. These instructions are separated in the program with the use of the internal relays linked to the slave outputs.

All of the slave outputs are linked to internals relays beginning at M300. These relays are turned on or off depending if the machines are on or off. For example, if machines 1&2 are turned on, internal relays M301 and M312 are switched on, which signal M49 (see Figure 5.27). If M49 in on and M1 is pulsed the first "TO" instruction is used to send a signal to the central controller to indicate that machines 1&2 are on.

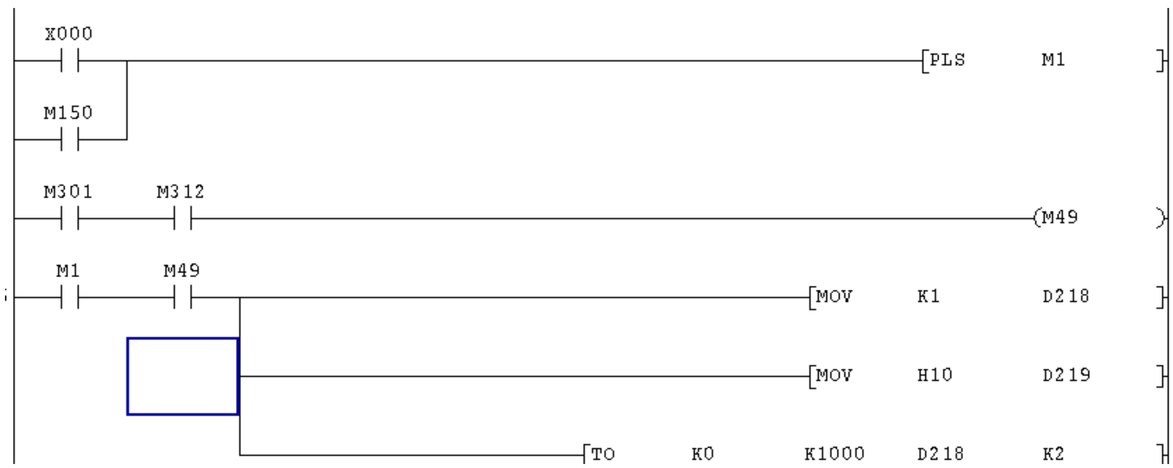


Figure 5-27 "TO" instruction

6 Machine Automation and Machine Integration

Elements of the machine automation in relation to the control programming were presented in Chapter 5. This chapter discusses in detail the automation of the grinding and lapping machines and their integration into the project. Also detailed is the AS-I fieldbus network and how it is used as a medium between the central controller and the machines on the plant floor. The design, construction and installation of the measurement display unit is also outlined in this chapter.

6.1 Grinding Machine Incorporation

This section of the chapter discusses the existing method of machine control and the modifications made to maintain a closed loop system control. The proposed method of machine control would have to possess the capacity to:

- Receive parameter altering command signals from a central controller.
- Generate digital feedback of the current load for overload control.
- Generate digital feedback of the ram hydraulic pressure for MRR control.
- The machine must also have the capacity to be controlled in a manual mode.

6.1.1 Existing Grinding Machine Control

One of the first technical challenges of the project was the implementation of the automatic adjustment of the grinding machine panel. The grinding machine panel controls 3 main outputs. These are an indicator light, the main drive that controls the rotating grinding stones and the ram which controls the distance between the two rotating grinding stones thereby controlling the material removal rate (MRR). The control of the ram is done by means of a closed loop system. The existing means of control is carried out using a control meter relay (manufacturer- Beede Electrical instruments) which has two extra needles. These extra needles represent the variable upper and lower current limits to be used when the machine is grinding in the original automatic mode. It operates as follows:

A vane attached to a moving coil of a Panel meter movement interrupts an infrared beam as the indicating pointer moves up scale and passes the set pointer. This interruption changes and state of the phototransistor attached to the set pointer, and switches an electronic circuit that either energises or de-energies the output relay. As long as the indicating pointer remains above the set pointer, the electronic circuit remains switched. As the indicating pointer falls below the set pointer, the electronic circuit returns to its former state. The basic mechanical construction of a panel control meter relay is a standard d'Arsonval meter movement, with an infrared source and phototransistor module mounted directly on the set pointer as in the mechanical drawing in Figure 6.2. The set pointer position is determined by the adjustable dials (See photograph in Figure 6.2). A change of phototransistor voltage changes the input signal to a steady state voltage comparator that energies or de-energises the output relay as demonstrated in Figure 6.1. (Diagram from the Beede control meter relay manual)

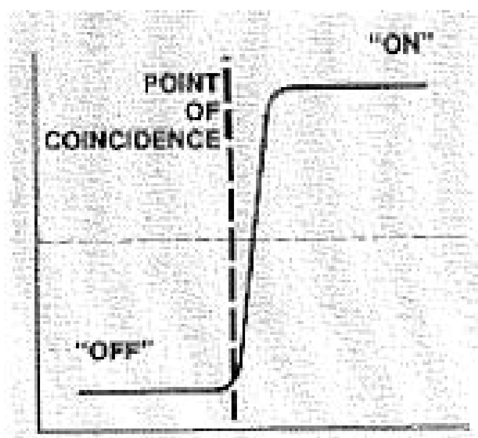


Figure 6-1 The change in phototransistor voltage

Optical latching of either relay or solid state output is provided by means of a positive feedback within the electronic circuit. The panel control meter relay is designed to inherently fail safe. The output relays are normally connected so the relays are energised in the "safe" condition, below a high set point and below a low set point. In case of a power failure or malfunction, the relays will de-energise. When power is restored, the unit will automatically provide the correct relay position. If required, a panel meter control relay can be wired so the output relays are energised on the opposite side of the set point.

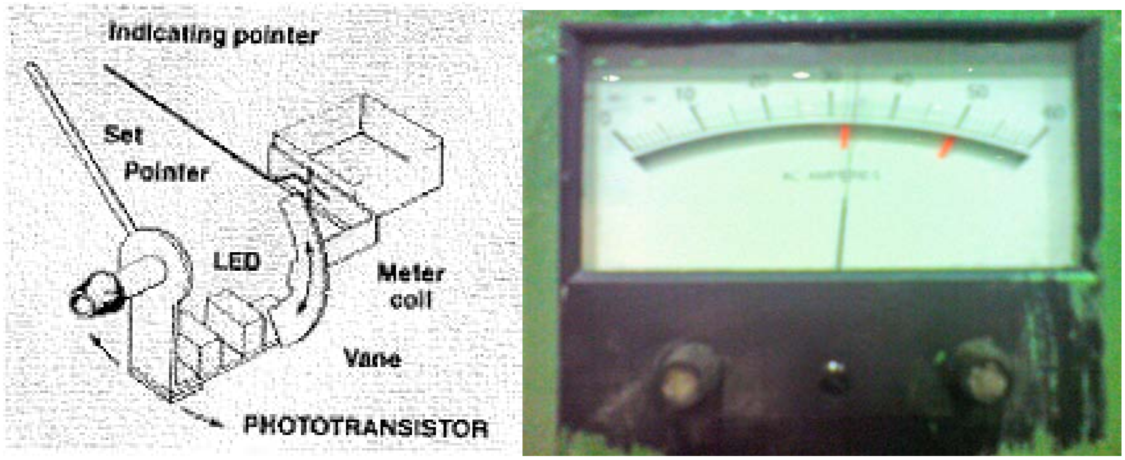


Figure 6-2 Mechanical drawing and photograph of Beede control meter relay

It was decided after some initial investigations that the existing machine panel would have to be completely rewired and the current method of adjustment would be replaced with a PLC linked with an A-D converter. The option for manual operation of the machine would be retained is case of a failure in the automated system. Monitoring of the machine's working parameters in terms of motor current and ram pressure would be carried out with the aid of an analogue current and pressure transducer. It was felt that a PLC system would be most suitable due to its flexibility and its ability to function in harsh working environments. It was considered that this would result in a safer and more accurate means of machine control than any hardwired (non-programmable) alternative automated control system that could be put in place.

6.1.2 Analogue to Digital Converter

An FX2N-4AD analogue to digital converter PLC module was used. This module has a capacity of four analogue inputs and consequently ample scope for adjustment and flexibility (only where immediately required). The module would convert the motor current and ram pressure analogue process signals into digital values which could then be monitored within the data registered of the PLC. This digital input would be compared with set digital numbers which represent the machine set point parameters. Figure 6.3 displays a photograph of the installed PLC and A/D Converter. A schematic circuit diagram of the re-wired grinding Panel can be seen in Appendix L.

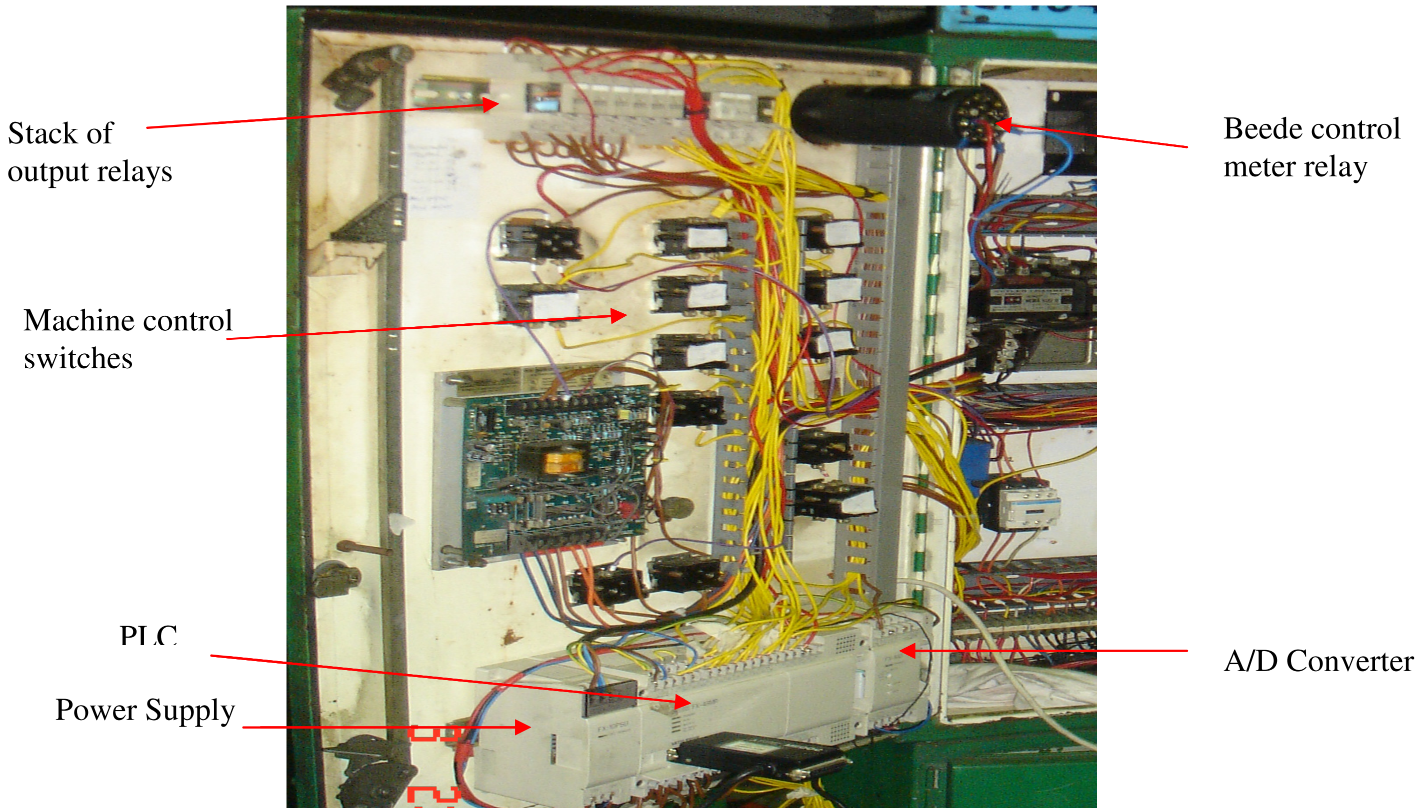


Figure 6-3 Photograph of installed PLC and A/D Converter

6.1.3 The Current Transducer

As mentioned earlier the current transducer is fitted around one phase of the 3-phase supply to the main drive motor. The formula to calculate power usage was applied (P=VI). This determined that the potential current load which is in the region of 93 amps. A Sentry 200 series current transducer was sourced (see Figure 6.4) that was capable of handling this current. This transducer can produce an analogue signal of 4-20 milliamps or 0-10 volts to represent a current load of 0-100 Amps.

Figure 6-4 Sentry 200 Series Current Transducer

6.1.4 Automatic Emergency Stop

As suggested in Chapter 5 one of the most costly and dangerous problems that occurs within grind is the breaking of a grinding stone. The most likely reason of this occurrence is when an odd size ball gets into the batch. With the proposed system the current load and the ram pressure are constantly measured and so allows for an emergency stop system to intervene when selected parameter set points are crossed. Monitoring the current from the motor was the most effective way to achieve this goal in terms of performance. When an oversize ball entered the grinding stones the increased diameter of the oversize ball meant that the pressure on the stones was significantly increased. This implies that the load on the motor increased rapidly. With the use a special internal plc relay (M8034) the system can disable all the outputs of the PLC when the motor current load reached dangerous levels thus stopping the grinding machine. Resetting this relay causes the machine to go to manual so as to avoid the risk of the machine starting up while an oversized ball is in the stones.

6.1.5 The Pressure Transducer

The relationship between the working pressure of the grinding stone and the stock removal is approximately linear. Even though there are many variables throughout the process of grinding, testing has shown that by maintaining a set pressure a predictable amount of stock is removed. The current load is not as linear as the pressure because from the start of the grinding process to the end the balls can marginally vary in shape (out of round) and draw more or less current depending on the level of roundness. The roundness or lack thereof, is created due to varying pressures through the process of grinding. Because of this the working pressure is required as a digital input to the automated system to maintain a more predictable process. To monitor the working pressure, a pressure transducer was installed in the hydraulic system. This generated a direct feedback of 0-10 volts which represents the range of machine working pressures. This system can be calibrated with a 0-10 volt signal and a potentiometer. Figure 6.5 displays a photograph of the installed pressure transducer.

Figure 6-5 Pressure Transducer

Typically the central controller will request a particular machine to maintain a certain pressure. The system will have five different working pressures to choose from. The chosen pressure will be picked based on where the previous sample measurement is situated on the control charts. When the central controller decides on the optimum working pressure of the grinding stone a signal is sent via the AS-I network to an input on the grinding machine PLC.

6.1.6 Testing modified Control Panel in the Lab

The project plan specified that the first ten months of development would be carried out in the laboratory at WIT; therefore, a grinding machine control panel was installed in the Laboratory. This was to allow for the prototyping of different design and development idea. The control panel was rewired with the PLC and A/D system. The PLC program was written and a simulation of the Machine operation was developed. A simulation of both the movement of the ram and the analogue signal from the transducers was required. To simulate the movement of the ram, a small portable hydraulic ram was connected to the panel hydraulic system. A dial potentiometer was used to simulate the analogue input signal. This was connected to the A/D converter and it replicated the 0-10 volts signal from the transducer. The panel control meter relay was left in place as a visual aid to the technicians but was disabled the automatic control feature of the device.

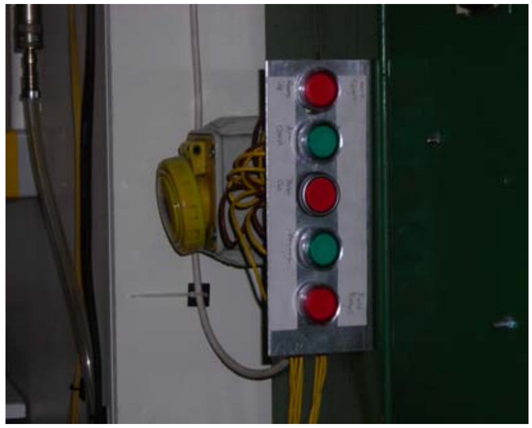


Figure 6-6 field trial override system

Within the completed automated system the capacity to change the grinding stone working pressures exists. This is controlled from the central controller via the AS-I network. At any time any one of six inputs to the PLC is turned on to maintain a precise operating pressure. Within the laboratory, during the early testing stage to simulate the control of the working pressure changes a bank of manual push button switches were mounted to the panel to change between the predetermined working pressures. Figure 6.6 displays a photograph of installed bank of push button switches.

6.1.7 The Retrieval and Propulsion system wiring

The grinding machine PLC also controls the operation of the grinding machine ball retrieval and propulsion system. For the control of the retrieval and propulsion system, a separate cabinet was constructed to contain the operational pneumatic valves required. This cabinet is situated behind the main grinding machine control panel. Figure 6.7 shows a photograph of the retrieval and propulsion control cabinet.

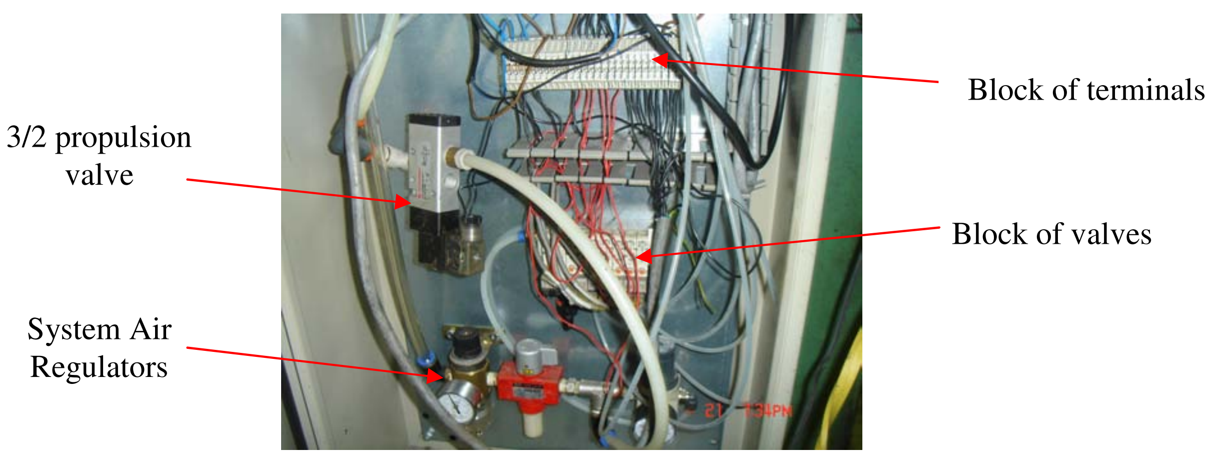


Figure 6-7 Retrieval and Propulsion control cabinet

A multi-core cable connects a 24volt DC supply and a block of outputs from the grinding machine PLC to the terminal rail within this cabinet. Using this terminal rail the solenoids of the valve block and the 3/2 propulsion valve are connected to individual output on the grinding machine PLC. The air regulators for the retrieval and propulsion system, as well as the shut off valves are also suited in this cabinet to facilitate a portable control system.

6.2 Lapping Machine Incorporation

After all aspects of the automated system were tested on the first grinding machine the next objective was to double the work load of the prototype system by incorporating a second. This would double the workload on the network and central controller giving some indication of how well the system would manage a larger scale project. It would require the elaboration of the overall control programme. The sequencing of more than one machine would be a significant step in the creation of a multi machine system.

One of the issues that occurred during testing of the first grinding machine was the level of sample ball roundness produced in the grind process. Due to significant stock removal rates associated with the grind process, the production ball would be more oval and out of round during the grinding process as opposed to any other process from grind to finished product (see Fig 6.8). The problem with the product from the first machine is that it gave rise to a lack of real challenge in terms of accurate results from the measuring instrument.

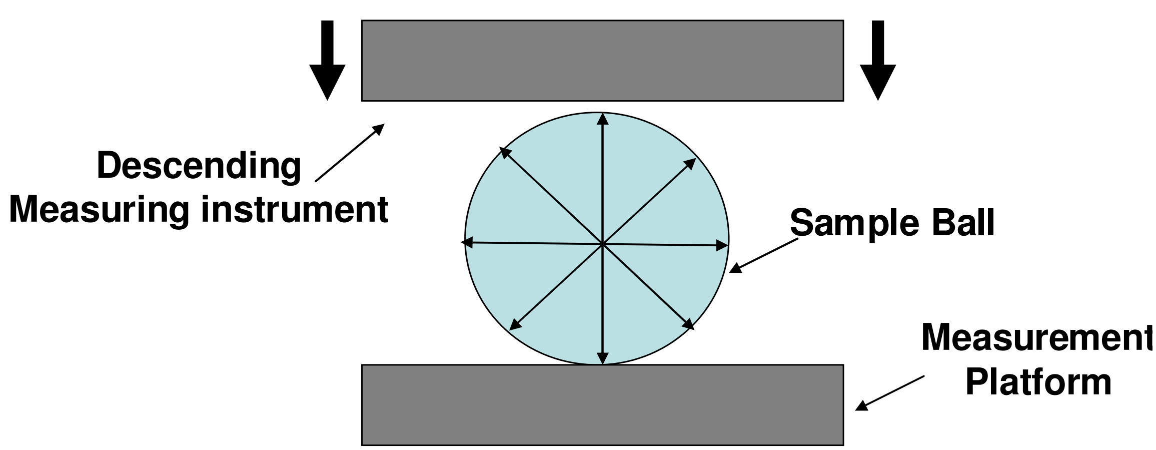


Figure 6-8 illustration of infinite point to point measurements

The second issue with testing the samples from the grind process is that the distance in which the measuring instrument must move is 150μm to allow for 130 μm of stock removal over the course of the grind process. To allow for more stringent testing of the measuring instrument a smaller range of measurements and measuring instrument movement would be preferable. The amount of stock removal from the grinding process to the finish product is as follows:

- **GRIND: 130 μm**
- **FIRST LAP: 20 μm**
- **SECOND LAP: 10 μm**
- **THIRD LAP: 3 μm**

Third lap was deemed the best process from which to sample due to its low stock removal rate and level of product roundness. A machine which produces 11.5mm balls was chosen from third lap as the second machine. This machine was chosen because this particular ball size was in high demand at the time of system installation which gave a higher rate of machine activity and more opportunity to sample. 11.5mm diameter product would also test the versatility of the generic retrieval, propulsion, transfer and delivery systems as it is 2mm smaller in diameter than the product sampled on the grinding machine.

The grind process is more concerned with stock removal whereas third lap is a polishing and finishing process. The main differences between the grind machines and the machines used in third lap are as follows:

- The lapping machine has a variable speed drive as opposed to a single speed drive in the grind machine. The stone R.P.M is less in lapping than in grind.
- The working pressure range of the lapping machine (600psi – 800psi) is less than that of the grinding machine (1000psi – 1400psi).
- The coolant used in the grinding process is a water based coolant as opposed to an oil based coolant used in lapping.
- The grinding process works with a grinding stone to ring contact on the balls and the lapping process works with a ring to ring contact.

6.2.1 Sampling Equipment Installation

As outlined in Chapter 3 the retrieval and propulsion systems for the lapping machine were upgraded based on the testing carried out on the retrieval and propulsion systems installed of the grinding machine. The adjustments made, resulted in a more robust and reliable system.

As the lapping process has a very low amount of stock removal and the product finish quality is high, the machine working parameters do not vary as much as the more rugged grinding process. As the lapping process has fixed working parameters, there was no necessity to install a means of feedback control to this machine. For this reason the existing control of the lapping machine was not altered. One advantage of this is that, any alteration made to the lapping machine could be easily reversed if this particular machine was not to be part of the larger scale project to follow. The retrieval and propulsion systems could also be easily transferred to another machine.

As there is no machine parameters controls associated with the central controller in this case (no feedback required), a simple control cabinet was constructed to manage the sampling from the lapping machine. A photograph of the lapping machine retrieval/propulsion system control cabinet is shown in Figure 6.9A. Within this control cabinet are:

- The PLC to control the operation of sample retrieval and propulsion.
- The main circuit breaker of the control cabinet.
- The 3/2 propulsion valve.
- The valve chest for the control of the retrieval system mechanical functions.
- The system air regulators and filter.

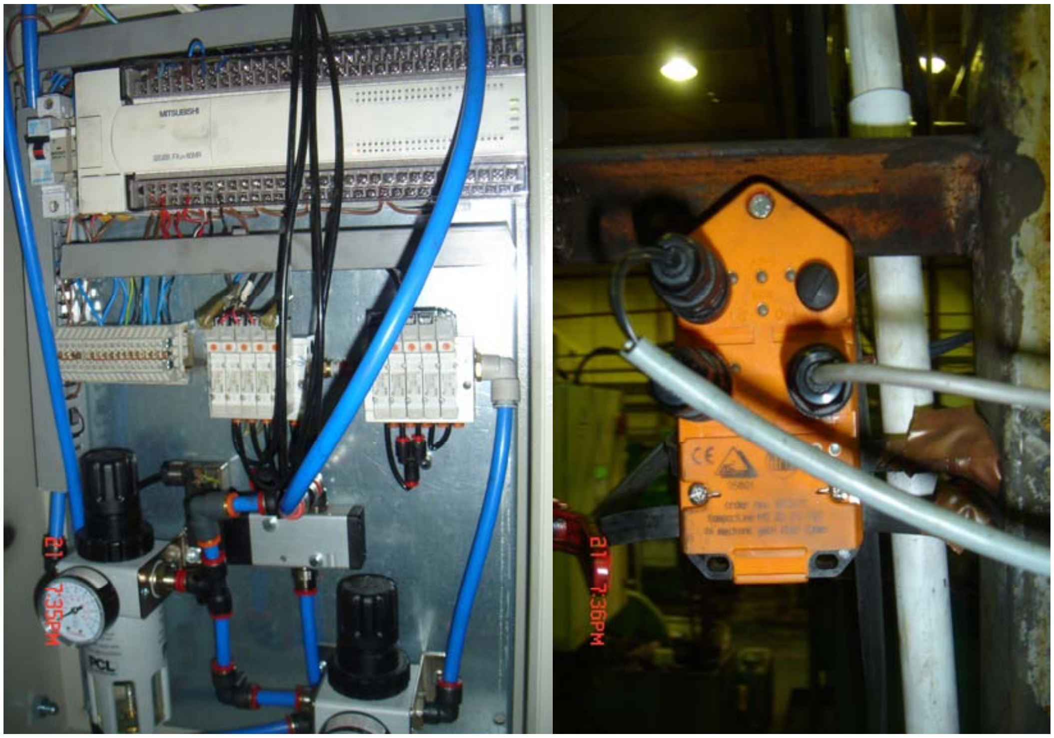
A.  B.

Figure 6-9 lapping machine control cabinet and associated network slave

The current AS-I network was extended across the production plant to this third lap machine to allow the central controller to communicate with the retrieval system and signal the start of the sampling process. An AS-I slave with two inputs and two outputs was fitted on the AS-I transmission cables near the lapping machine and addressed to the AS-I master. The outputs and inputs of the AS-I slave were then wired directly to PLC (See Figure 6.9B).

Even though the retrieval and propulsion system control is isolated, the central controller still needs a signal from the lapping machine to represent the machine status at the point of sampling. To do this a 24volt DC signal was required at an input to the PLC when the lapping machine is in operation. This signal was sourced from the inverter control module. The inverter is the device which controls the variable speed of the machine. Within the inverter control module is a relay coil which is closed when the machine is turned on. This relay is used as a switch to signal the PLC when the machine is turned on. The PLC control is outlined in detail in Chapter 5.

6.3 AS-I Field Bus Network

The section of the chapter discusses the network installed on the plant floor, and its means of communication between the Central Controller and the grinding machine controllers.

6.3.1 Introduction

In this project an AS-I (actuator- sensor interface) network is used as a medium between the central controller and the machine controllers on the plant floor. The AS-I system is a low level fieldbus network, which is controlled by a master controller and communicates with the grinding machine controllers through the use of slaves mounted on the AS-I transmission cable. The AS-I transmission system cable consists of two unshielded two wire cables which can be extended to cover the entire grinding area. One of these cables is used to distribute power to the slaves and the other is used to transmit the data signals. Up to 124 input and outputs are possible on the AS-I interface system.

The data transfer is bi-directional between the central controller and the AS-I network controller. The signals being sent from the central controller represent the request to retrieve samples and the command to change the machines operating parameters. The signals being sent to the central controller represent the operating status of each machine at the time of sampling. The AS-I network is extremely flexible as it is uses as a conventional tree structure which can incorporate star, line and ring structures.

As shown in Figure 6.10, a slave can be mounted anywhere on the data transmission system cable. The command signals are sent between the network controller and these slaves, in the form of 24 volts which, when switched, can be linked directly to the inputs and outputs of the grinding machine controllers (PLC's). This particular version of AS-I network is limited to 32 slaves which allows for 124 binary input and 124 binary outputs. Several AS-I networks can be installed and connected to a central sever using a Profibus or Ethernet network.

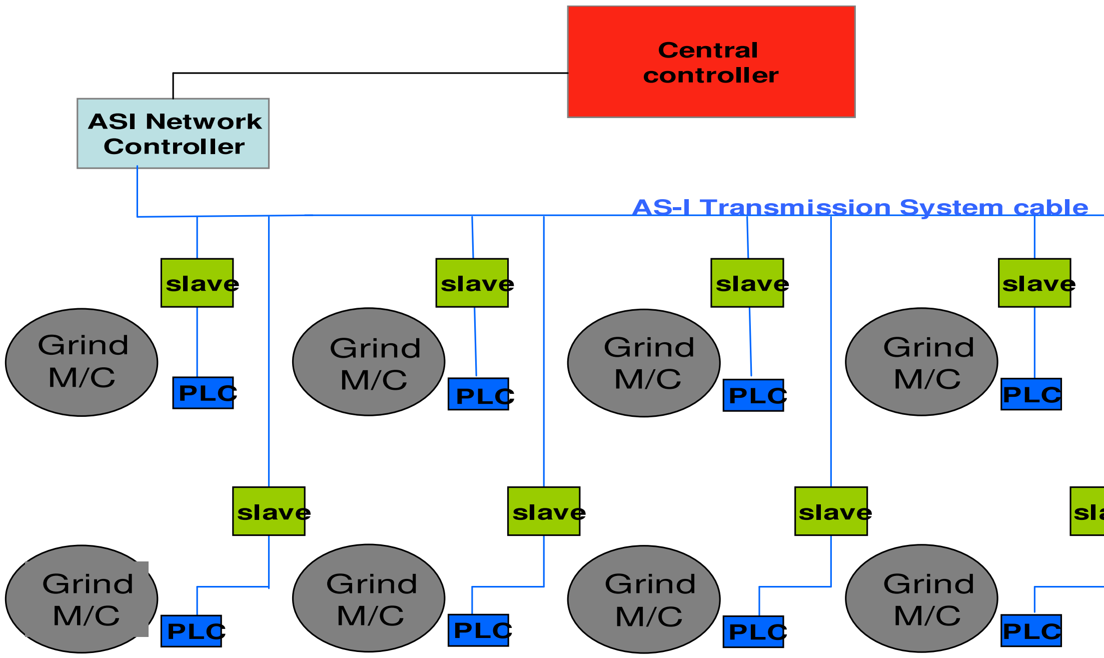


Figure 6-10 AS-I network tree structure

6.3.2 The AS-I Network controller

The AS-I network controller communicates with the central controller via the RS232 serial port. Within the AS-I network control system (See Figure 6.11), there are four main hardware components:

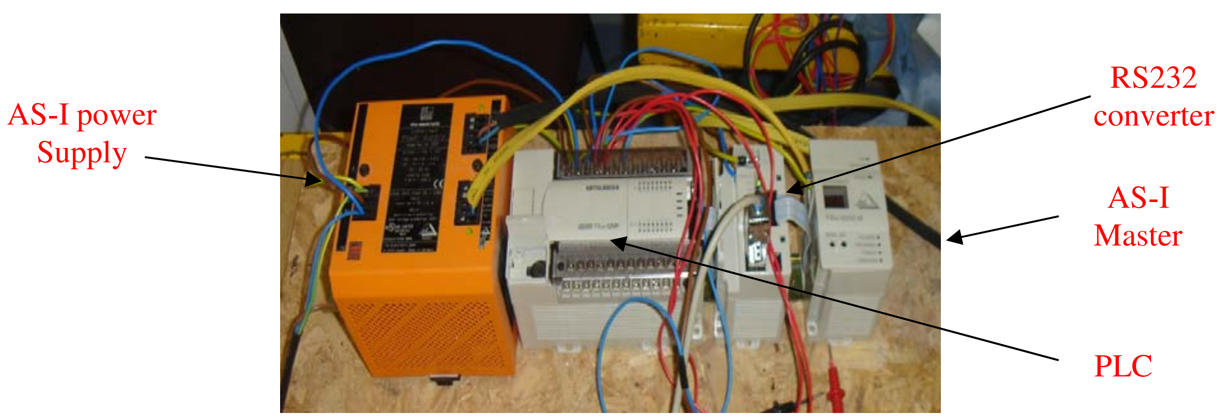


Figure 6-11 AS-I Network Controller Hardware

- The AS-I network power supply
- The Programmable logic controller (PLC)
- The AS-I master module
- The RS232 converter module

The Mitsubishi FX2N PLC is essentially a microprocessor encased in a module. The module contains its own power supply, a microprocessor and a number of opto-isolators. It allows for a good degree of flexibility with an inexpensive method of wiring and programming most modern manufacturing machines. The use of opto-isolators ensures that the microprocessors are well protected from spikes and surges in the power supply. It also isolates the microprocessor from the inputs as well as the outputs which can be operating on a different voltage. The RS232 converter module and the AS-I Master module are connected to the PLC one after another, in a daisy chain effect. The FX2N range can allow for up to eight external modules to be added in this way. This Mitsubishi FX2N PLC has 16 outputs and 16 inputs.

The AS-I network power supply, supplies 24 volts to the AS-I Network Controller Hardware and the AS-I transmission system cable. The RS232 converter module converts the central controller signal to a compatible format for the PLC program (explained in the Systems control Chapter). This allows the central controller to send specific numbers which represent specific commands (i.e. number 76 may represent the command for machine 1 to pick as sample from the batch). If a specific number enters the monitored data register on the PLC, an internal relay is programmed to activate and send signals to a slave input assigned to the request.

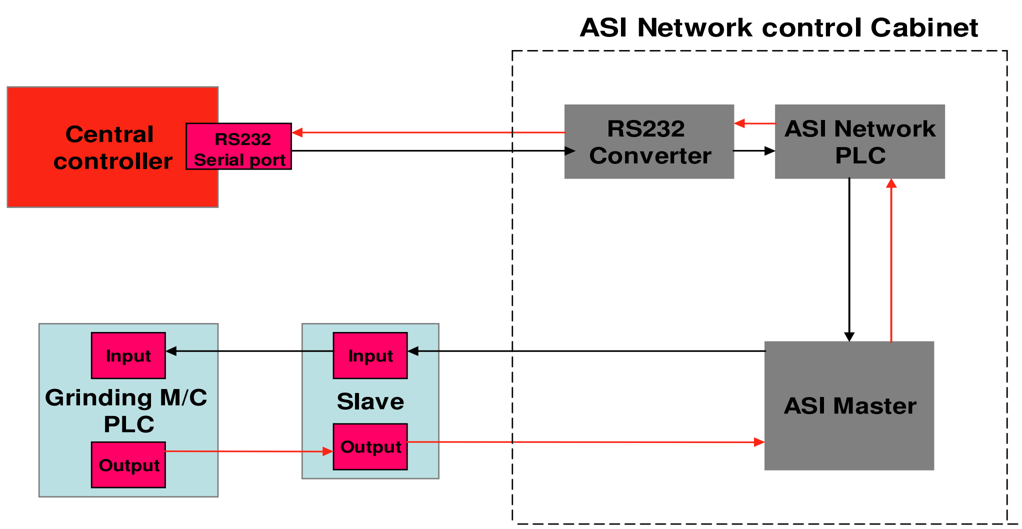


Figure 6-12 Command signal direction of the AS-I network

The AS-I master continuously scans the network of slaves on the AS-I transmission cable and alerts the PLC to the logic of the slave outputs. The slave outputs are activated by the grinding machine PLCs and represent the operational status of the individual machines. When the PLC program receives this data it is converted and sent to the central controller in binary form by the RS232 converter. The AS-I Master module also delivers the central controller commands from the AS-I network PLC to the machine controllers via the AS-I transmission cable and slaves. The direction of the input and output command signals can be seen from the block diagram in Figure 6.12. The programming and control of this system is discussed in detail, in Section 5.8 of the System control Chapter.

6.3.3 The AS-I Transmission System

The AS-I transmission system consists of three hardware components which are connected to each other and to the application via three interfaces. These components are:

- The transmission system (cable)
- The slaves
- The master

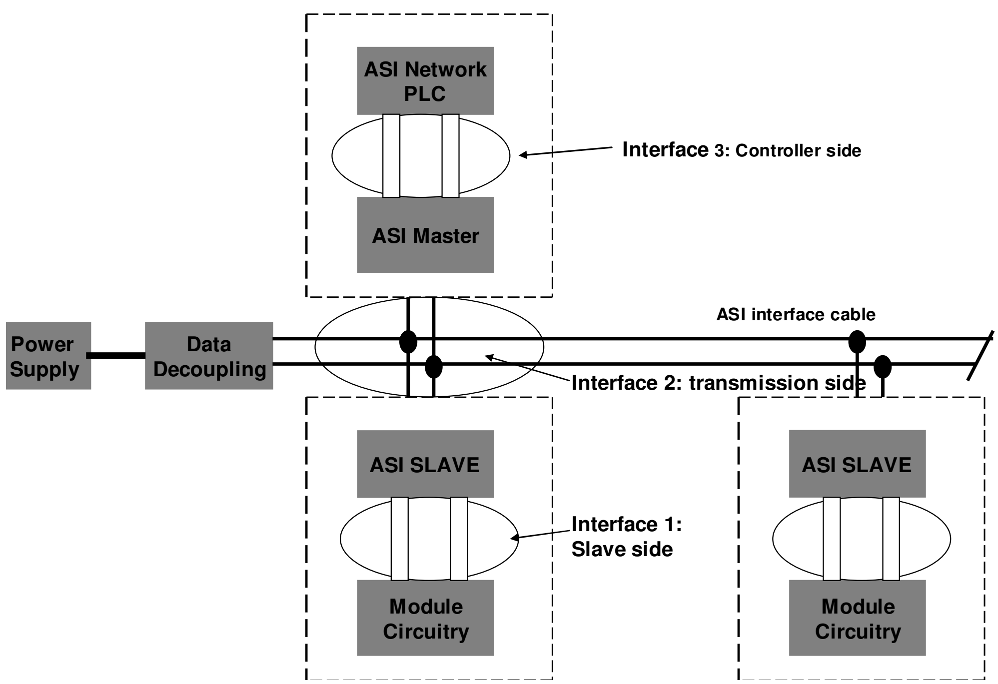


Figure 6-13 the AS-I transmission system

The transmission system consists of a power supply, the data decoupler and the AS-I cables which links the slaves to each other and to the Master. There are three separate interfaces in the transmission system as can be seen from Figure 6.13.

At Interface 1, the slave establishes the connection to the grinding machine controller. AS-I systems are designed so that the slave function can be completely integrated into the controlled machine. There are four data ports available at interface 1 of the slave which depending on the defined I/O configuration, can be used as input ports, output ports or for bi-directional data exchange. Figure 6.14 shows an installed AS-I slave with 1 input and 2 outputs wired directly to the grinding machine PLC.

Figure 6-14 Installed AS-I slave

At Interface 2, each slave is connected to the AS-I transmission cable and should communicate trouble free with the master and not interfere with the communication of the other slaves and the master. At the terminals of the slave the transmission system provides an operating voltage of between 26.5 and 31.6 volts DC. Figure 6.15 shows the terminals of the slave and the way in which the cable is connected to the slave.

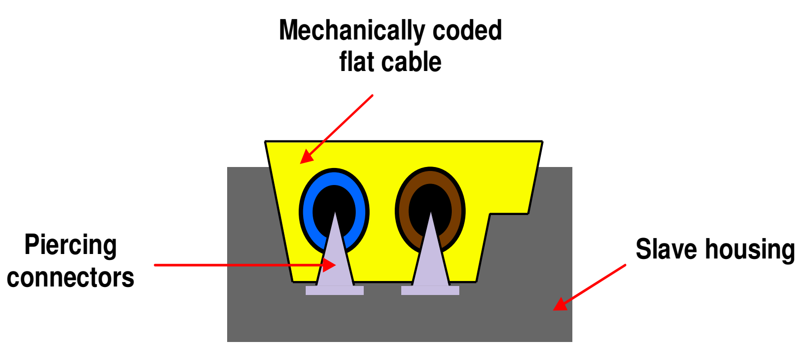


Figure 6-15 The connection terminals for the AS-I slave

The slave at this point can draw current from the AS-I interface network in order to supply its own electronics, and the signal to the input of the grinding machine PLC. The AS-I Transmission System cable is a shielded two core cable that is moulded so that it can only fit into the AS-I modules in one orientation. The maximum cable length without repeaters is 100 meters. A maximum of two repeaters may be used if the cable needs to be extended, which brings the maximum transmission system length to 300 meters.

At interface 3, the master establishes the connection to the AS-I network controller which can be a PLC, a PC or a coupler to a higher level fieldbus system, Furthermore, the master controls the data exchange via the AS-I transmission cable and carries out the necessary management functions.

Figure 6-16 handheld slave addressing tool

6.3.4 Addressing the Slaves

The addressing of a slave can be done in two ways:

1. It can be done using the master module request "Change_Operating_Address" via the AS-I interface line. It is important that during the addressing procedure only one slave with the address "zero" is connected to the network.

The second method is to use a special handheld addressing tool as shown in Figure 6.16. The functions of this tool are limited to the most necessary. Only one slave at a time can be addressed to the network. The slave is directly attached to the addressing tool via the adapter head. The master module keeps sending the "Read_I/O_Configeration" message to all the slave addresses until the slave has answered. The address of the slave is then shown on the display. The ascertained address can then be changed to the desired new address using the plus, minus and write buttons.

6.3.5 RS232 to RS4222 Interface Converter

At the time of the project installation it was decided to locate the central controller with the temperature normalization and measurement station in a discrete location away from the plant floor. The main reason for this was to avoid the noise and vibration created by the machinery on the plant floor which would cause interference to the measurement instrument. The main problem with this location for the central controller was the distance from the grinding area, and the inability of the AS-I network to function over distances exceeding 100m without repeaters. The solution to this problem was to locate the complete AS-I network and its controller in the grind area of the plant and install a Category 5 shielded twisted pair cable as a medium between the central controller and the AS-I controller.

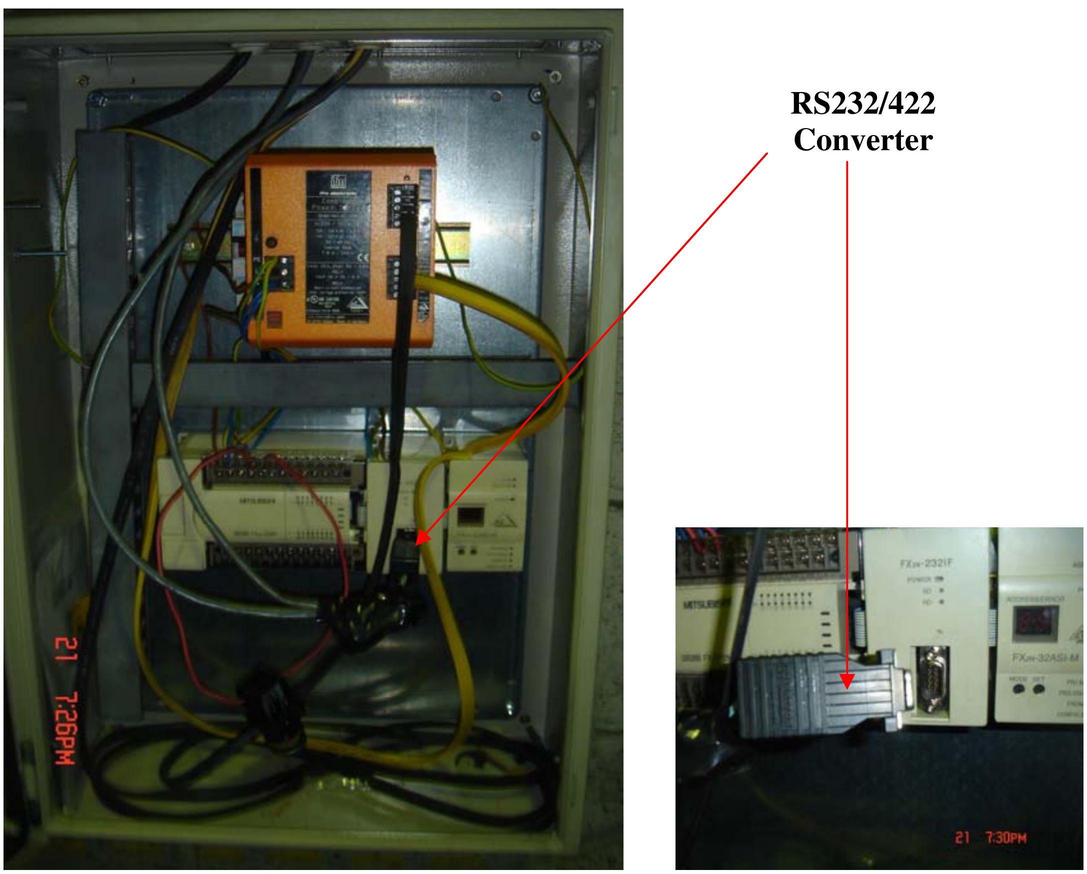


Figure 6-17 Installed AS-I Control Cabinet and RS232/422 converter

The RS422 signal can be transmitted up to 1300 meters. Figure 6.17 shows a photograph of the installed AS-I control network cabinet and the RS232/422 converter and Figure

6.18 displays a block diagram of the hardware connections between the central controller and the AS-I network controller.

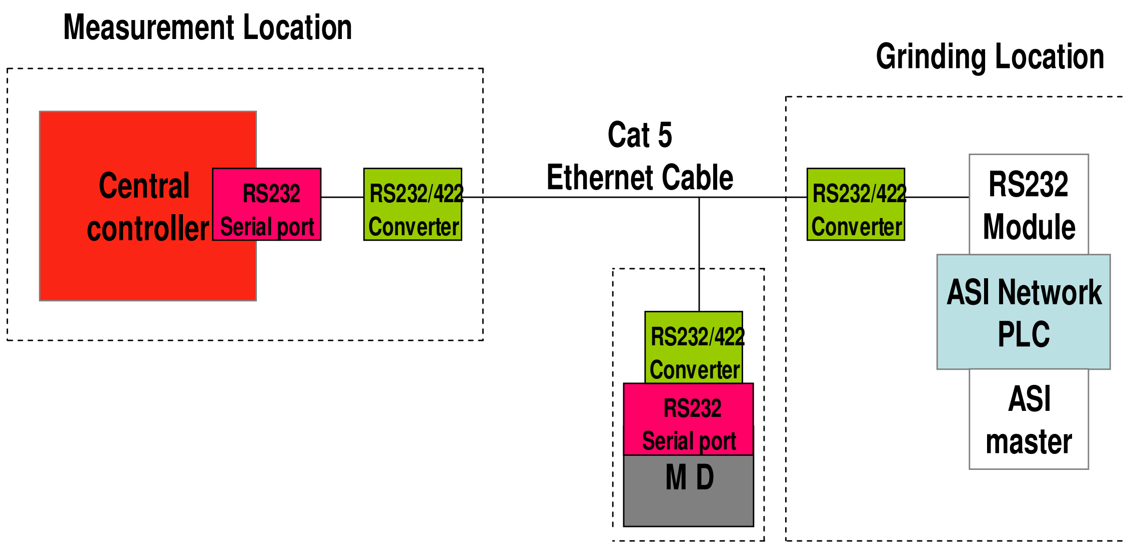


Figure 6-18Hardware connections from central controller and AS-I controller

As the maximum transmission distance of an RS232 signal is 20m the signal was converted to an RS422 to extend the transmission distance and converted back to RS232 at the signal destination. This allowed for the central controller to transmit a signal to anywhere on in the production plant. The specific converter used is a model 222N9 RS232 to RS422 interface converter which allows asynchronous PCs, terminals and laptops employing the RS232/DB-9 interface to communicate with devices using RS422 balanced electrical signals [26]. In the case of this project the signal is converter at both ends, as the devices being used also require an RS232 signal. Facilitating bi-directional over two twisted pair, the model 222N9 draws all necessary operation power from data and control voltages on the RS232 interface. The model 222N9 support data rates to 19.2 Kbps. The Measurement display detailed in the next section of this chapter uses the same means of communication to the central controller as the AS-I Network; therefore, the RS232 to RSS422 converter is also utilised at this point.

6.4 Measurement Displays

The idea for the measurement displays (MD) came about during the testing phase. It was realized that the level of automation through a larger scale system would progress over a period of time. Because of this fact, it was felt that a measurement display at the grinding machines would enhance visibility and thereby confidence in the project. An automated display unit on the machines would allow the technicians to make comparisons between the automated system measurements and the manual measurements plotted on a cut-down chart. This display would present the average measurement of the sample taken by the automated sampling system and the time in which the sample was measured. This data would be sent out directly after the measurement is taken (at the same time as the measurement is being saved to a file). The automated measuring system results could then be easily compared to the manual charted cut down graphs for each machine.

At the stage of the project development when the display unit was being considered the AS-I control network was in operation and was communicating with the central controller via the Category 5 cable. It was deemed feasible to use this existing cable for both the AS-I network and as a medium between the central controller and the measurement display unit. A block diagram of the proposed measurement display communication lines in shows in Figure 6.19.

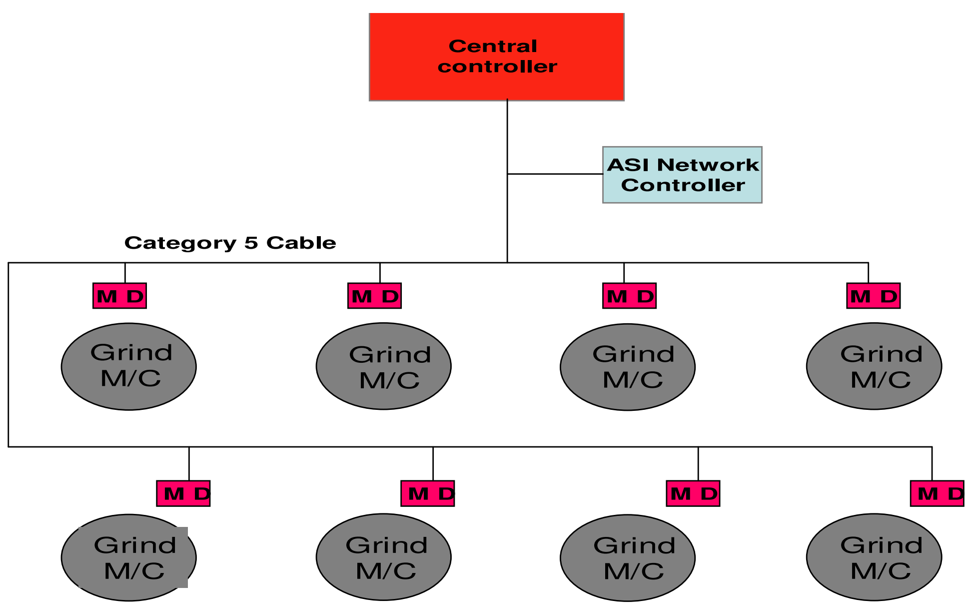


Figure 6-19 block diagram of proposed measurement display communication

6.4.1 Design of the Measurement Display unit

An electronics expert was contracted the build a custom made LCD measurement display unit with the required design specifications for the system.

This unit is designed to display the measurements from the central controller (LabVIEW program). The unit scans all inputs on the RS422 line for an 8bit preamble, which is sent by the central controller just before a measurement data is sent out. After this preamble is recognised, it then takes the next string of data and processes it into the format Date, Time, and Ball measurement. It then converts this code into ASCII format and displays it on the LCD screen. The whole process is done using a programmed 16 bit PIC Microcontroller, working with a 5MHz instruction cycle. The Main components in the electronic circuit are the PIC Microcontroller, (MAX232) for converting the RS232 signal into a TTL level for the PIC to read, and a voltage regulator to regulate the voltage supply for the PIC. The schematic drawing and PCB layout for the circuit board are shown in Appendix J.

As shown in Figure 6.20 the electronic circuitry of the custom made measurement display unit was fitted in a heavy duty electrical junction box and the LCD screen was fitted into the lid of the box. Displayed on the LCD screen are the measurement time and a measurement size correct to four decimal places. A holding bracket was then fabricated to mount the measurement display unit to the associated grinding machine. A Schematic and PCB layout for the measurement display board can be seen in appendix J.

Figure 6-20 measurement display unit

7 Results and Analysis

This chapter outlines the results from all aspects of the custom made ball transfer system including retrieval, propulsion and delivery. Also detailed are the test results from the stock removal versus machine working pressure trials. The fluid temperature normalization results are also outlined.

7.1 Introduction

When the project commenced the outlined work was segregated into sections as follows:

1. Ball retrieval
2. Ball propulsion
3. Ball delivery
4. Pilot Plant development and temperature control
5. SPC control

Each of these work areas was prototyped during the course of the project and each prototype was tested and improvements made until an adequate level of performance was achieved.

7.2 SPC control

This section of the chapter outlines the data gathered for the construction of the cut-down chart associated with the 13mm steel balls.

7.2.1 Grinding Tests (pressure versus stock removal)

To automate the feedback of the machine working parameters a cut-down chart was required against which to plot sample measurements. The point at which the measurement was plotted on the chart would determine if the process was in control and what changes needed to be made to the grinding stone working pressure, if any. Whilst cut-down charts were in use in the manual system it was felt that these might not be accurate enough for the automated system.

The first step in constructing the cut-down chart was to gather a significant amount of data to predict the levels of stock removal achievable while controlling the process. The main objective of the grind process is to remove as much stock as possible while maintaining an acceptable level of quality in the product. The quality of this product is established by the level of ball roundness. This is accessed by measuring the range of diameters, from highest to lowest, on one sample within the batch; the higher the range of diameters the lower the quality.

As outlined previously the current tolerance for finished product is 1micron and the target tolerance for this project is 0.1micron. The range of working pressures used in the grinding process varies from 800 to 1400p.s.i. On start-up the pressure is ramped up to 800 for the first 30 minutes and then the machine is switched to automatic and controlled by the panel current meter. The meter is generally kept between 30 and 40 amps which will exert working pressures on the stone between 1100 and 1400p.s.i depending on other machine variables such as groove depth on the grinding stone.

To construct a reliable cut-down chart three main factors were accessed:

1. Amount of stock removal per hour.
2. Level of ball quality.
3. Efficiency regarding the electrical current requirements per increment of 100p.s.i.

Test Duration (Hr)	STOCK REMOVED mm/Hr	Out of Round (Max-Min)		
0	0	0.00062992	**Statistics**	**micron**
1	**0.01126236**	0.00059944	Average	2.89200
2	**0.0129667**	0.00046228	Range	1.61900
3	**0.01317498**	0.00099568	Max	3.40300
4	**0.01276858**	0.0010414	Min	1.78500
5	**0.01593596**	0.00138684	Cp	157.46600
Average	**0.013221716**	**0.000852593**	Cpk	1.82200

Table 7-1 Stock removal result for 1200p.s.i

The pressure versus stock removal testing phase took place over a two week period. The testing phase concentrated on five different working pressures. The test began on a new batch at 1000p.s.i with sample being measured every hour over a 5 hour period. The mean of the stock removal was recorded. This test was carried out in the same manner for the other four working pressures (1100p.s.i, 1200p.s.i, 1300p.s.i and 1400p.s.i). All results are shown in Appendix H.

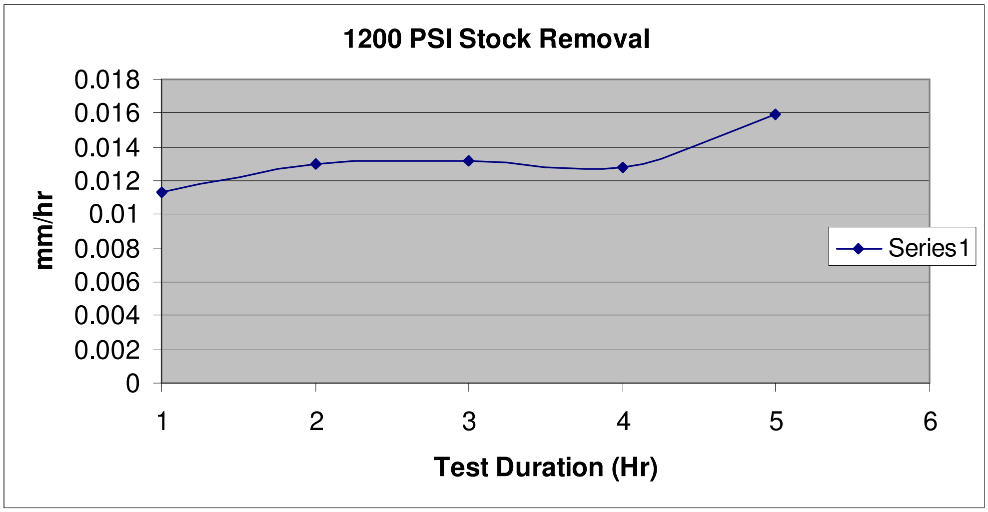


Figure 7-1 stock removal rate for 1200p.s.i test

Considering the three main factors outlined above a working pressure of 1200p.s.i was deemed to be most efficient with a stock removal of approximately 12.5 microns/hour (see Figure 7.1) while still maintaining an acceptable level of quality (see Figure 7.2). Although the level of quality is acceptable based on the required tolerances, the trend of the results in Figure 7.2 may warrant more extensive research but this is outside the scope of this particular project.

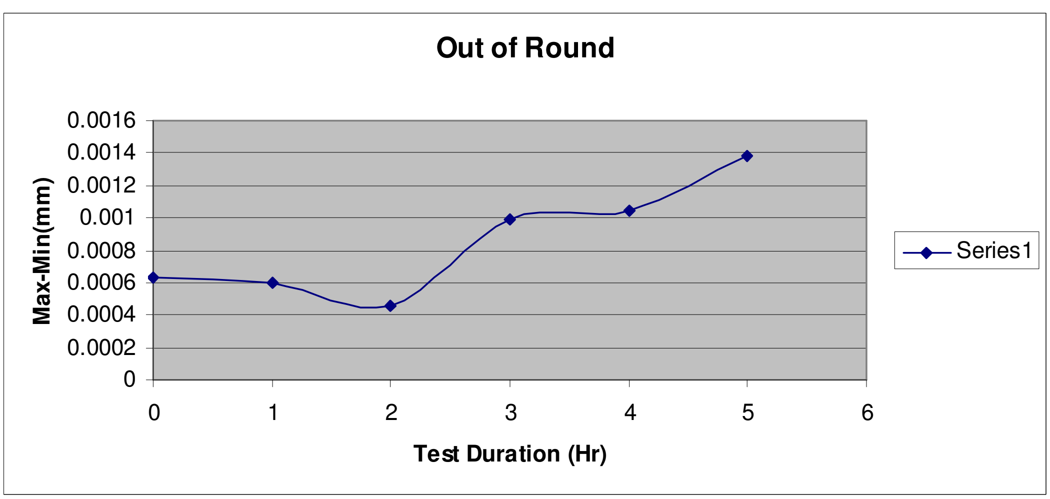


Figure 7-2 level of quality for 1200p.s.i test

7.2.2 Cut-down charts

Cycle Time	Stock Removal mm/Hr	Actual Diameter	UCL	LCL
0	0	13.6652	13.68019903	13.650201
1	0.0064	13.6588	13.66879936	13.6488006
2	0.0127	13.6461	13.65609936	13.6361006
3	0.0254	13.6207	13.62569968	13.6157003
4	0.0254	13.5953	13.60029968	13.5903003
5	0.0254	13.5699	13.57489968	13.5649003
6	0.0140	13.5559	13.55789959	13.5539004
7	0.0140	13.5419	13.54389959	13.5399004
8	0.0140	13.5279	13.52989959	13.5259004
9	0.0140	13.5139	13.51589959	13.5119004

Table 7-2 Gathered data for 13mm cut-down charts

Based on the collected data taken during the testing phase, the specifications for a 13 mm ball cut-down chart are shown in Table 7.2. The points for the upper and lower control limits were calculated using the following formulas, where $\overline{X}$ is the sample mean, and σ is the standard deviation.

Upper Control Limit $= \overline{X} + 3.09\sigma$ Lower Control Limit $= \overline{X} - 3.09\sigma$

Cycle Time	Stock Removal mm/Hr	Actual Diameter	UCL	LCL
0	0	13.6652	13.67519936	13.6552006
1	0.0064	13.6588	13.66879936	13.6488006
2	0.0127	13.6461	13.65609936	13.6361006
3	0.0127	13.6334	13.64339936	13.6234006
4	0.0192	13.6142	13.62419936	13.6042006
5	0.0254	13.5888	13.59879936	13.5788006
6	0.0254	13.5634	13.57339936	13.5534006
7	0.0254	13.538	13.54799936	13.5280006
8	0.0254	13.5126	13.52259936	13.5026006
9	0.0140	13.4986	13.50859936	13.4886006
10	0.0140	13.4846	13.49459936	13.4746006
11	0.0140	13.4706	13.48059936	13.4606006

Table 7-3 Existing data for the current 13mm cut down chart

Table 7.3 displays the data used for the configuration of the existing cut-down charts of the 13mm ball grinding process. There are disparities between the cut-down specifications of the existing cut-down chart and the proposed cut-down chart. The reasons for this are:

1. The amount of stock to be removed in the current grinding process is less than that required when the original cut-down charts were configured due to process enhancements over time. Therefore, the process is now less time consuming.

2. The method of control for the manually operated machines is the electrical current panel meter resulting in varying working pressures. The proposed automatic control system maintains constant pressures between adjustments.

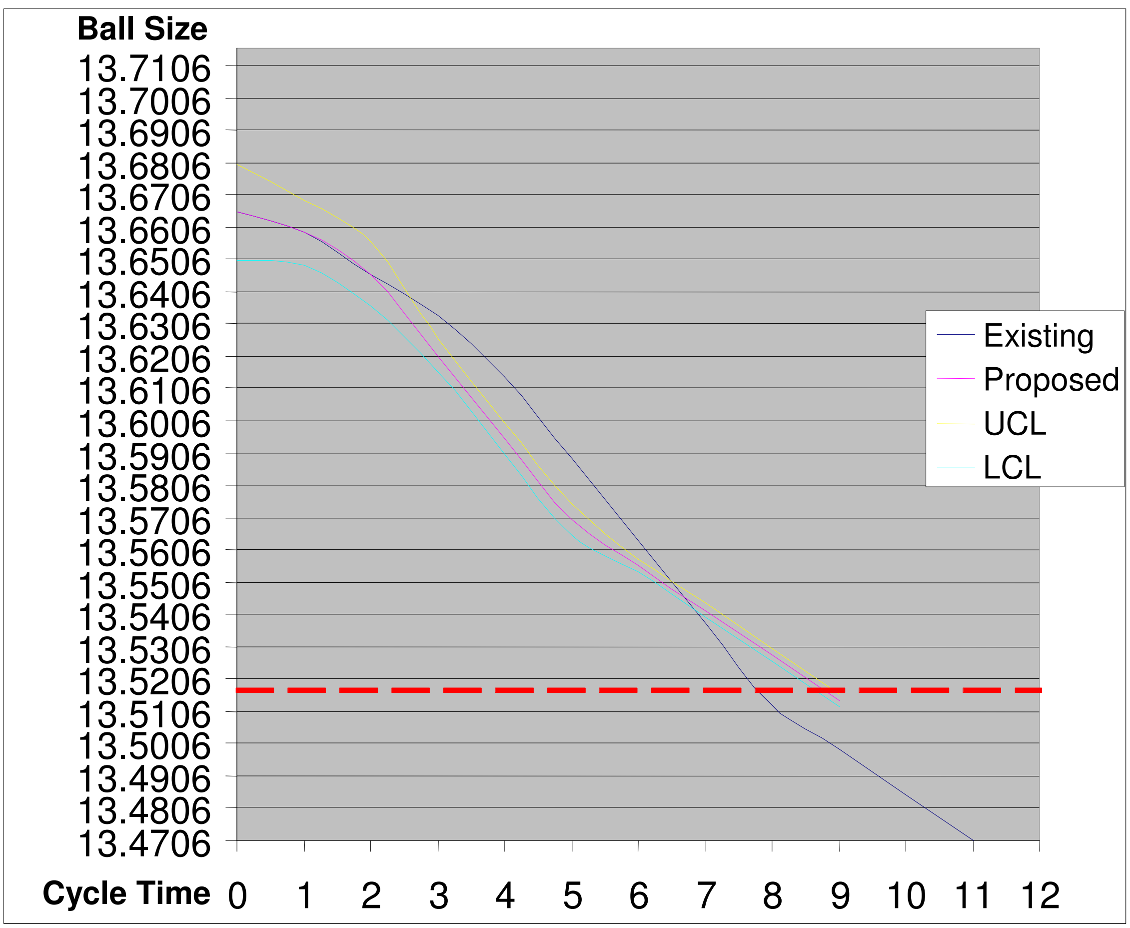


Figure 7-3

Figure 7.3 displays the proposed cut-down chart with the upper and lower control limits displayed and a comparison between the existing and proposed cut-down rates.

7.3 Grinding Machine transfer system test results

Throughout the prototyping of the transfer system the results were measured in terms of working repeatability. This section of the chapter discusses the level of repeatability throughout the different prototypes of the grinding machine transfer system. The test result of the finally installed working prototype is also outlined.

7.3.1 Grinding machine retrieval system results

As the retrieval system was prototyped the level of repeatability was insufficient until two key alterations were made to the system.

1. A ball blocker and sensor were installed to the end effecter. This modification secured the ball in the end effecter while the retrieval unit retracted from the grinding machine turn table. Before this installation the level of successful ball retrieval was approximately 75%.

2. The downward incline of the piping (for gravitational feeding) between the retrieval system and the propulsion system was limited due to the location of both systems and the grinding machine itself. This led to an occasional failure in the ball delivery to the propulsion chamber. It was eventually established that this was due to the fact that some residual coolant from the samples would deposit on a section of pipe (which was close to level). As the coolant built up slightly, it would act as a resistance to the sample and cause a blockage. This problem was difficult to identify as the piping was installed under parts of the grinding machine and the blockage did not occur frequently. To counteract this problem the pipe was perforated at the level section to release the coolant.

After these modifications were made to the grinding machine retrieval system the unit was tested over a 200 repetition cycle with no failure. During the ongoing testing of the complete system the retrieval system has not failed to deliver the sample to the propulsion chamber. Due to limited time for testing and the harshness of the working environment it is unknown how many repetitions the system is capable of before servicing is required.

7.3.2 Grinding machine propulsion system and piping results

As previously stated in Chapter 3, the propulsion system consists of an automatic entry valve to a propulsion chamber with an air supply on one side and the entry to the piping network on the other. The entry valve was prototyped from a custom valve operated with a pneumatic actuator, to a rotary valve controlling an on/off manual valve. Even though the first idea was much less expensive it lacked effectiveness during longer tests.

Table 7.4 shows the results from the propulsion system test with a 4% failure rate. Over 100 tests the system failed to deliver the sample on 4 occasions due to pipe separation. The main problems with the transfer system relates to the piping network from the propulsion system to the temperature normalizing tank. The piping was installed in 4 metre lengths of 20mm diameter PVC pipe. This was the most convenient method of installation due to the degree of difficulty in reaching the overhead cable trays where the piping would be located. However, with sectioned piping, the issue of section separation was possible.

Test num	Result	Test num	Result	Test num	Result	Test num	Result	Test num	Result
1	+	21	+	41	+	61	+	81	+
2	+	22	+	42	+	62	+	82	+
3	+	23	Fail	43	+	63	+	83	+
4	+	24	+	44	+	64	Fail	84	+
5	+	25	+	45	+	65	+	85	+
6	+	26	+	46	+	66	+	86	Fail
7	+	27	+	47	+	67	+	87	+
8	+	28	+	48	+	68	+	88	+
9	+	29	+	49	+	69	+	89	+
10	+	30	+	50	+	70	+	90	+
11	+	31	+	51	+	71	+	91	+
12	+	32	+	52	+	72	+	92	+
13	+	33	+	53	+	73	+	93	+
14	+	34	+	54	+	74	+	94	+
15	+	35	+	55	+	75	+	95	+
16	+	36	+	56	+	76	+	96	+

17	**Fail**	**37**	**+**	**57**	**+**	**77**	**-**	**97**	**+**
18	**+**	**38**	**+**	**58**	**+**	**78**	**+**	**98**	**+**
19	**+**	**39**	**+**	**59**	**+**	**79**	**+**	**99**	**+**
20	**+**	**40**	**+**	**60**	**+**	**80**	**+**	**100**	**+**

Table 7-4 Propulsion system test results

Each failure in the test was and due to a random section of pipe separating. After each failure the pipe was reinforced. This pipe separation was due to the high impact on the bends of the piping network created by the samples travelling at high speed and secondly, the lack of proper reinforcement on the coupling joints of the 4 meter lengths of pipe. The piping network therefore had to be dismantled and reinforced with a high strength adhesive to prevent any air leak and breakages. The same test was conducted again and the results delivered 100% performance.

7.4 Lapping Machine transfer system test results

As mentioned earlier the design of this system was a modification of the grinding machine transfer system, based on observations made during the system tests. The benefits of these modifications were; improved system strength and exspected increased length of working life. These modifications are explained in detail in Chapter3. The same test was carried out on this transfer system and the results (Table 7.5) were convincing with only one fail on the 3rd repetition due to a lack of air supply pressure to open the propulsion valve. After increasing the pressure, 100 % repeatability was achieved.

7.5 Delivery system results

This section of the chapter discusses the working repeatability within the three sections of the delivery system (release, injecting and sorting). The problems with the delivery system related to the issue of multiple ball sizes being delivered through the same system.

7.5.1 Ball release system results

The working repeatability of the ball release system was extremely reliable as it functioned mostly on gravity feeding and timer controlled pneumatic valve operations. Approximately every one in two hundred samples would jam at the end of the guide funnel as they entered the exit valve out of the temperature normalizing tank. This was due to the rare event of several balls from the five ball sample reaching this exit at the exact same instant. This exit was therefore widened as much as possible to alleviate the problem. If the problem continues then a sequenced delay of the sample balls might be possible.

7.5.2 Ball injecting system results

Table 7.6 displays the results of a test carried out to assess the system working repeatability. This test was carried out on the smallest ball in the size range for a more stringent test. On the 7th, 9th ^{and} 67th repetition the injection system inserted two balls instead of one.

Test	Result	Test	Result	Test	Result	Test	Result	Test	Result
1	+	21	+	41	+	61	+	81	+
2	+	22	+	42	+	62	+	82	+
3	+	23	+	43	+	63	+	83	+
4	+	24	+	44	+	64	+	84	+
5	+	25	+	45	+	65	+	85	+
6	+	26	+	46	+	66	+	86	+
7	Fail	27	+	47	+	67	Fail	87	+
8	+	28	+	48	+	68	+	88	+
9	+	29	+	49	+	69	+	89	+
10	+	30	+	50	+	70	+	90	+
11	+	31	+	51	+	71	+	91	+
12	+	32	+	52	+	72	+	92	+
13	+	33	+	53	+	73	+	93	+
14	+	34	+	54	+	74	+	94	+
15	Fail	35	+	55	+	75	+	95	+
16	+	36	+	56	+	76	+	96	+
17	+	37	+	57	+	77	-	97	+
18	+	38	+	58	+	78	+	98	+
19	+	39	+	59	+	79	+	99	+
20	+	40	+	60	+	80	+	100	+

Table 7-5 Ball injecting test results

The ball injecting system had multiple problems concerning the ball size variation. The main problem with the ball injecting system is that it consists of many components attached to a metal base. These components are mainly pin cylinder used for holding and releasing the balls to the measuring platform and with the slightest movement of any of these components, the potential for too much or too little space in a holding area arises. The ball injection system is precisely assembled to cater for the range in ball sizes and when misaligned, the occurrence of two 10mm balls being released instead of one may exist. To maintain this precise pin cylinder alignment the attachment bracket components on the base of the ball injecting system would have to be assessed and adjusted if required, on a periodic basis to prevent system failure. During these tests there was no bracket readjustment done after failure. The results from this test were unacceptable; subsequently, the holding pin cylinder was relocated and tightened and retested; 100% repeatability is now achieved.

7.5.3 Ball sorting system results

The ball sorting system was modified on numerous occasions to gain an acceptable level of working repeatability. After each modification the repeatability of the unit was tested until an acceptable level of confidence was gained. The two main modifications were:

1. The re-fabrication of the sorting unit floor, switching to stainless steel instead of aluminium. This ensured an even floor lift by eliminating wear in the treaded hole for attaching the lifting cylinder.

2. The slots which the balls fell into when the floor was raised were re-machined and rounded off. Occasionally when the floor lifted the calibration ball would get trapped between the sorting pin cylinder and the straight edge leading towards the slot. When this edge was rounded the ball moved toward the slot every time.

7.6 Temperature control Results

As mentioned previously, the temperature between the measuring tank and the temperature normalizing tank required precise control to eliminate the risk of thermal expansion difference between the samples and the calibration balls. The temperature difference between any locations within these tanks needs to be as minute as possible.

After the installation of the temperature control equipment and the required flow rate between the two tanks was established. Achievable tests were carried out to access the level of temperature control. It was found that the coolant temperature variation can be maintained to 0.1 ^{o}C throughout the body of coolant from the Measurement tank to the

Temperature Normalizing tank. The calculations below for the largest diameter component (13.5mm), prove that by maintaining this temperature variation, between the temperature normalizing tank and the measuring tank, there will be a max increase/decrease in component length of 0.0143µm which is well within the desired tolerance.

- The Coefficient of thermal expansion for 52100 chrome steel (α) = 10.6×10^{-6}
- The change in temperature (∂T) =0.1 ^{o}C.
- Component linear dimensions (L) = 0.0135×10^{6} meters
- The change in length = ∂ L

$$\alpha = \frac{1}{L}\frac{\partial L}{\partial T} \longrightarrow \partial L = \alpha \times L \times \partial T$$

$$\partial L = 10.6 \times 10^{-6} \times 0.0135 \times 0.1 \times 10^{6}$$

$$\partial L = 0.0143$$

The continued maintenance of this 0.1 ^{o}C variation when the whole plant is feeding into the system will have to be assessed at that stage and any necessary adjustments made to maintain performance.

8 Conclusions

Within this chapter the results are summarised and conclusions are drawn regarding the level of project success against the objectives. The project limitations and potential improvements are discussed and the recommendations are made for the next stage of the project.

8.1 Results Summary

The objectives were outlined at the beginning of the project and are numbered as follows:

1. Development of a temperature normalizing test rig for sample and reference storage, cooling and measurement.
2. Development of a sample component transfer system.
3. Control modifications of two machines.
4. Development of a system network and SPC control.

Each section of the project displayed an acceptable and convincing level of sucess. These results can be carried forward and analysed to assist with the development of an effective commercial system.

Pilot Plant development and temperature control

- The coolant temperature of the Temperature Normalizing Plant is maintained to less than 0.1 ^{o}C difference between any two points in the body of coolant.
- When the full heat load from the production machines is brought onto the system it will change the balance of course, so adjustments will have to be made to try to maintain this performance.

The sample component transfer system was developed in three sections:

1. Ball retrieval

- The first retrieval system developed displayed only a moderate level of success. The sensor and blocker pin cylinder components when added to the end effecter solved all the problems.
- The lapping machine retrieval system was of a similar design to the latter successful unit but was fabricated with durability and resilience in mind. This design also delivered 100% repeatability when tested.

2. Ball propulsion and piping network

- The final prototype of the ball propulsion system is a simple concept and will continue to delivered acceptable results as long as the entry valve has ample operating pressure and no air leaks exist in the propulsion chamber.
- The piping network gave numerous problems with leaks and joint breakages until the piping was reassembles with high strength glue. After the reassembly, the piping network withstood high pressure ball transfer tests with 100% efficiency.

3. Ball delivery

- The ball delivery system is sectioned between ball release, injection and sorting. The release and sorting systems functioned with 100% repeatability when tested. The ball injection system was at times problematic when dealing with the varying ball sizes.

Production machine control modifications

- The first grinding machine cabinet was completely rewired and fitted with a PLC and A/D converted which was capable of directly controlling the working pressure through the use of transducer. This means of control was also capable of communicating with the central controller for automatic working pressure readjustment and functioned successfully.
- It was decided to use a lapping machine for the second machine in the project. The control of this machine was not modified as feedback control was not required and stock removal was minimal. The envisaged benefits of utilising a lapping machine in the project were:

    1. To test the sample transfer system on more than one machine.
    2. To create more stringent tests on the measurement system with product of higher tolerances.

Both of these benefits have materialised and the integration of machines from two different areas of the plant has added confidence in the extension of the system to the rest of production.

System network and SPC control

- The developed SPC control is effective for automatic monitoring of the process and the feedback control to the two machines from which the samples are being taken. Its extension to more machines and eventually to the entire plant is very achievable.
- The amount of communication required for the two machines in this project is relatively low but the current system is considered to be capable of extension to deal with future traffic in the plant.
- The currently installed AS-I network system is satisfactory up to this point, but may be inadequate if the project expands to twenty machines or more as this particular model is limited to 124 input and outputs. The solution may be to upgrade to a more recent edition of AS-I network or to have more than one network in operation. If the amount of traffic on this network increases a more sophisticated system may need to be installed.

8.2 Conclusions

The main objective of this project was to develop a fully automated prototype system for the extraction, feeding and temperature control of product samples to a central measurement station complete with the feedback loop control of the production machines themselves.

The project was broken down into a number of distinct sub-projects, each of which was prototyped in the laboratory and then transferred on-site and installed on-line on two representative production machines. The feasibility and the level of complexity involved in the extension of this automatic sampling and measurement system for all the machines in the plant can now be seen clearly.

The development process to-date has been one of prototyping and then continuous improvement. This process of building, testing and continual improvement has resulted in a robust prototype system which will be extended with the addition of more production machines.

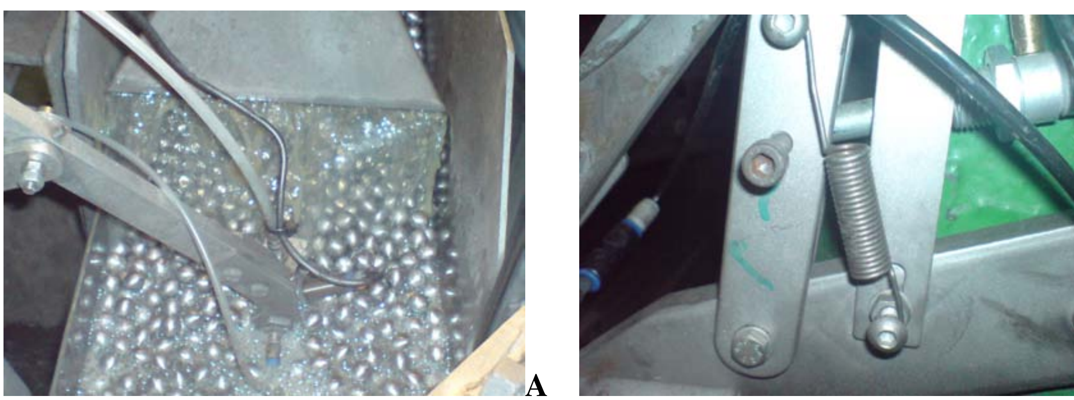
The objectives of the project were reached and the results can be used as the vital building block for the design and development of a commercial system. The Company are determined to press ahead with this. Some aspects of the project which may be reviewed and adjusted in the drive for wide scale implementation in the plant are discussed in the Future Work section of this chapter.

8.3 Future Work and Discussions

For the development of a commercial sampling and measurement system for a 24 machine process such as grinding (and indeed the entire plant), some system alterations are suggested below: these relate to the issues of the harsh industrial environment involved and considerations of the working life of the system as well as the safety and measurement tolerance improvement.

Safety:

The only safety issue outstanding with the test rig is the operation of the retrieval systems. As the air is transferred to the operating cylinder, the picking arm needs to move aggressively to extend and submerge the picking cup in the collection of balls (see Figure 8.1a). As this operation is controlled by the central controller which is located at the other side of the plant, there is no warning to indicate the retrieval system movement which leaves the technician exposed to possible injury. The issue also applies to the arm retraction process.



A B

Figure 8-1 retrieval system

To adhere to the industrial health and safety standards, a safety guard will need to be installed around every retrieval system. This guard will need to cover the retrieval system arm and the area in which the arm extends. Ideally, the guard would be locked and easily unlocked for maintenance. The guard would also act as protection to the retrieval unit.

Transfer pipe cleaning:

As the sample is being retrieved from the batch a minute amount of coolant may also be retrieved on the surface of the ball. As the ball in propelled to the temperature normalizing station it is thought that the coolant may accumulate, solidify and deposit on the inside of the piping over a large number of sample transfers. If this occurs the internal pipe diameter of the pipe will decrease and hinder the ball transfer process. This problem is predicted but remains to be seen as the system has not transferred enough samples to show any evidence of coolant deposition on the inside of the transfer pipe. If this problem arises over time, cleaning using a pigging system may need to be implemented. This method of pipe line cleaning is carried out by propelling bristled objects know as 'pigs', through each pipe line. The key issues for this are access for entry and exit of the 'pig' and any limitation on pipe bend radii demanded by the cleaning system.

Durable piping:

As this project progressed ongoing problems occurred with the PVC piping to the point where it was reassembled with high strength adhesive. This particular pipe was chosen due to its ease of installation and relatively inexpensive costs. For durable and robust piping network a more hard wearing material may be required to withstand the effects of wearing in the pipe over a longer operating period. The transfer pipe may need to be installed in a continuous length from each machine to the central location, rather than the currently installed sections of coupled 4 metre piping. This would rule out the possibility of breakages at the couplers, but would increase the installation difficulty.

Pin cylinders:

Throughout the Temperature Normalizing Plant both the samples and the calibration balls are located and held using pneumatic pin cylinders. This is a very effective and inexpensive method of controlling the location of the steel ball within the system. As some of the pin cylinders may be submerged in the Temperature Normalizing Plant coolant, the effect that the coolant may have on their seals will have to be considered. No evidence of any problem with this has been seen as yet. If this problem arises, the issue could be part of a preventive maintenance plan which replaces the pin cylinders periodically.

Injection system machining:

The component brackets on the current ball injecting system are assembled on the injecting system base. There tends to be a minute level of movement over time between the secured brackets and the base, which offsets the ball locating pin cylinders. These pin cylinder are precisely located to facilitate a generic system for the range of ball sizes. If the pin cylinder brackets move any distance the generic system becomes less reliable. In an approach to this problem, the holding brackets and the injecting system base could be machined from one piece of material. This would eliminate bracket movement.

Temperature Normalizing Plant Reconstruction:

To date, the Plant has been constructed through a series of prototypes and is very effective in its functionality. However, for a commercial system a new temperature normalizing and measuring station will need to be constructed. The scale of the new construction would be slightly larger but all the operational concepts could be taken from the test rig constructed in this project. This larger scale unit will allow for lids to be installed on the tank (not feasible with the test rig due to the height of the measuring instrument). Even though a filtration system would be installed, lids would be an essential part of any commercial system due to the potential for particles in the atmosphere depositing in the open tanks and affecting the extreme precision in the measuring instrument.

Temperature Normalizing Plant Control:

As the number of machines being controlled by the automatic sampling and measuring system increases there will be a greater demand for multiple lines of communication between the Temperature Normalizing Plant controller and the central controller. For the sampling of two machines there are some lines of communication required and these are hard wired. With two machines, communication is minimal as the PLC assigns the samples to their associated calibration ball and they are released together; however, when the number of machines being sampled increases a Supervisory Control and Data Acquisition (SCADA) system may need to be installed to allow the central controller to signal the PLC to sequence the release of specific samples and calibration balls to the measuring instrument. This software can be installed as an add-on package to the currently installed operating system (LabVIEW). The SCADA system can be directly linked to the Temperature Normalizing Plant controller to allow communication to be carried out with the use of tags which can operate any internal relays of the PLC.

Temperature controlled enclosure:

To isolate the measuring instrument and test rig from the harsh environment of the production plant floor, both were placed in a location with less noise and vibration. To gain maximum performance from the measuring instrument, further isolation may be necessary. This isolation may be achieved be means of an enclosed room. The benefits of this enclosure would be:

1. Complete isolation from the harshness of the production plant environment to optimise the capability of the measuring instrument.
2. Isolation from the production plant atmosphere which would decrease the likelihood of solid particles lodging in the coolant surrounding the measuring instrument.
3. Less difficulty with maintaining the coolant temperature control. As the demands on the measuring instrument (in terms of accuracy) increase (as expected), as the projects develops, the issue of equalising the sample and calibration ball temperature will become more important.

Sample return:

If a commercial unit is developed for a larger number of machines, a means of returning the sample to its batch after measurement may be required. This added function may be required as the automatic sampling and measuring system operates much more frequently than the current manual measuring process. Without a return system a large build-up of waste and a more significant loss of finished product would naturally occur. A return pneumatic propulsion system would be obvious, as this method of transfer is already in operation and its limitations are known. The one major issue in this process is that the product would have to be stored, cooled, measured and returned to the batch within 10 minutes to keep the returned ball at the same diameter as the rest of the batch and not cause problems for the grinding process upon sample return.

Finally, it should be stated that while each component in the system, as developed in the project, produced acceptable results in the trial tests that were carried out, it remains to be seen how effective the system functions over a longer time period. Only time will provide any guarantees in this regard. However in the spirit of the continuous improvement approach in the project, continual upgrading of the system in the future will produce a satisfactory system in the longer term. This project has delivered an excellent prototype starting point for the long term system.

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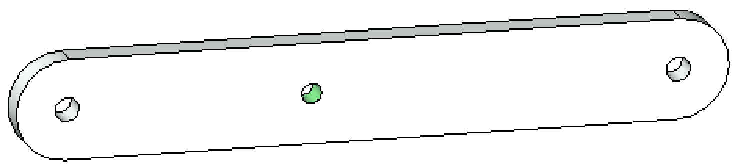
11 Appendix A (CAD drawings of retrieval system)

1. Side rail
2. Slotted link
3. Mounting rail
4. Spring
5. Top arm
6. Actuator
7. Bearing
8. PVC end box
9. Rear clevis mount.
10. Rod end
11. Assembled retrieval system



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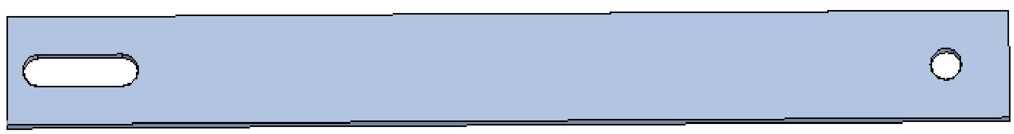

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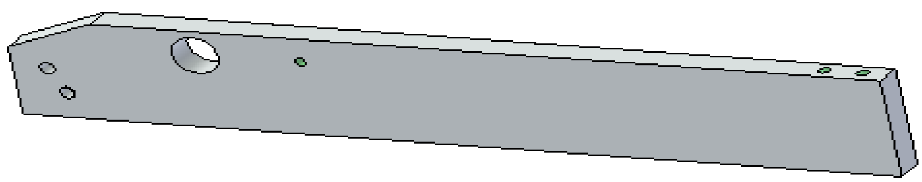

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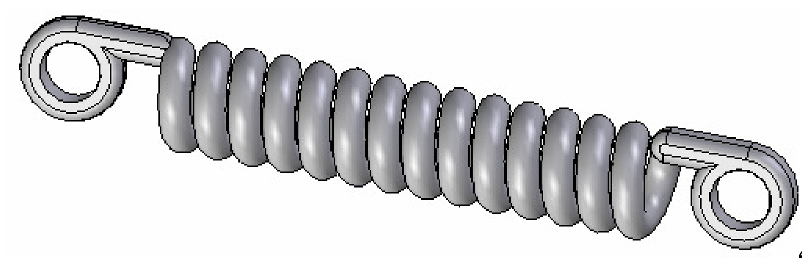

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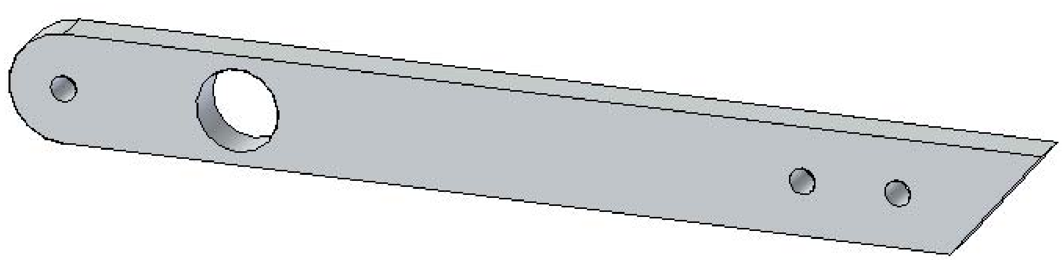

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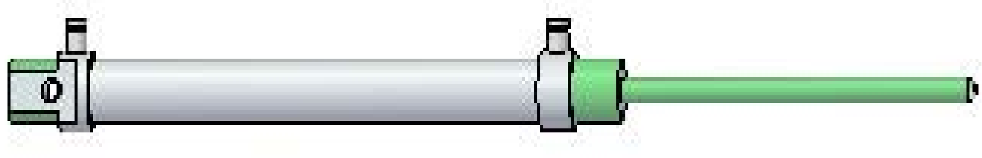

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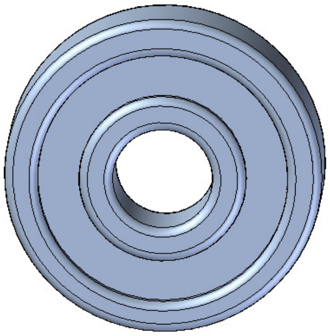

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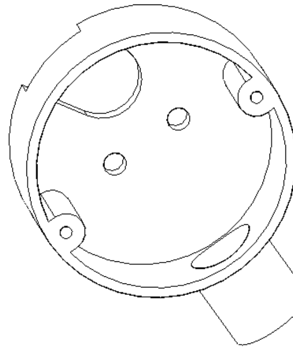

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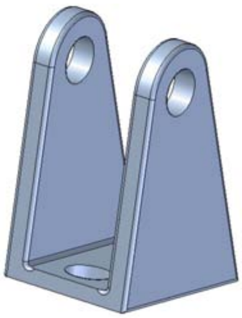

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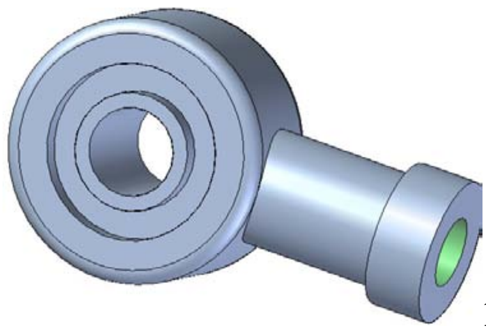

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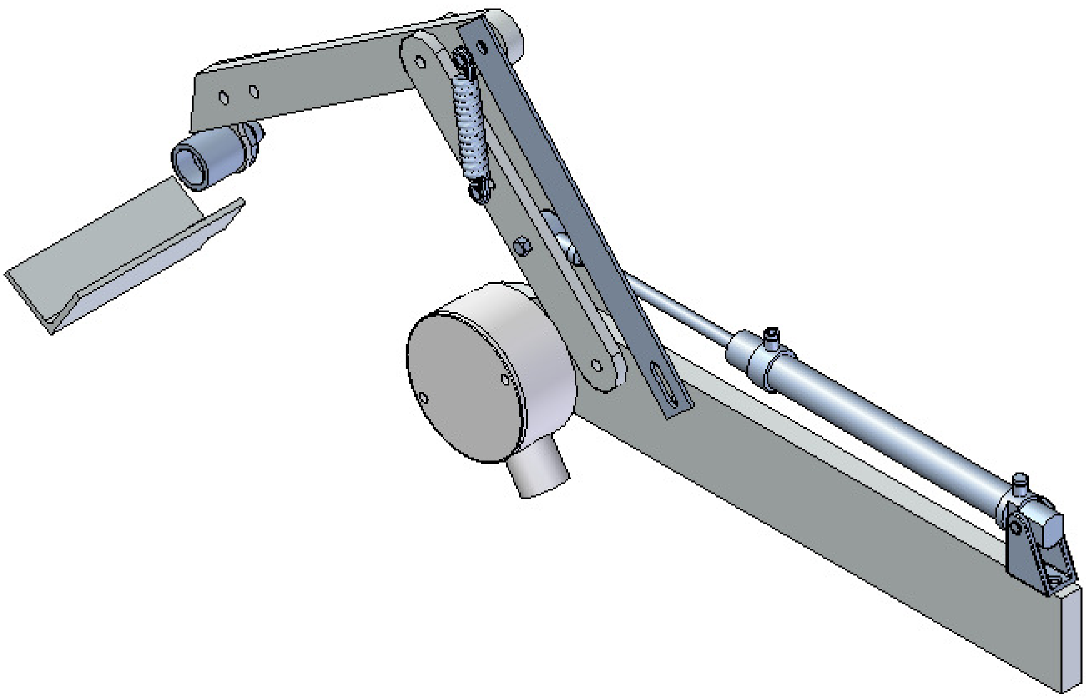

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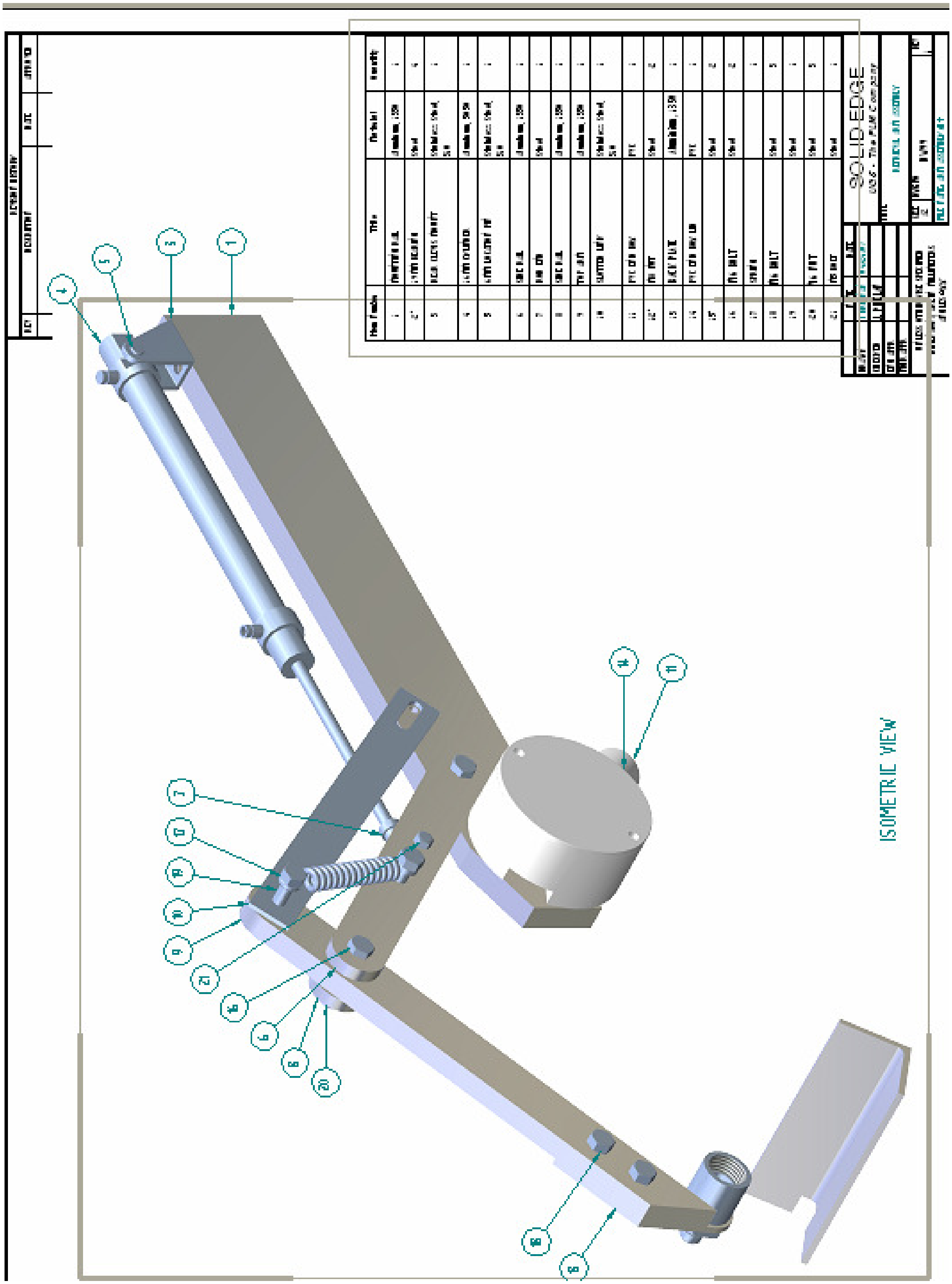
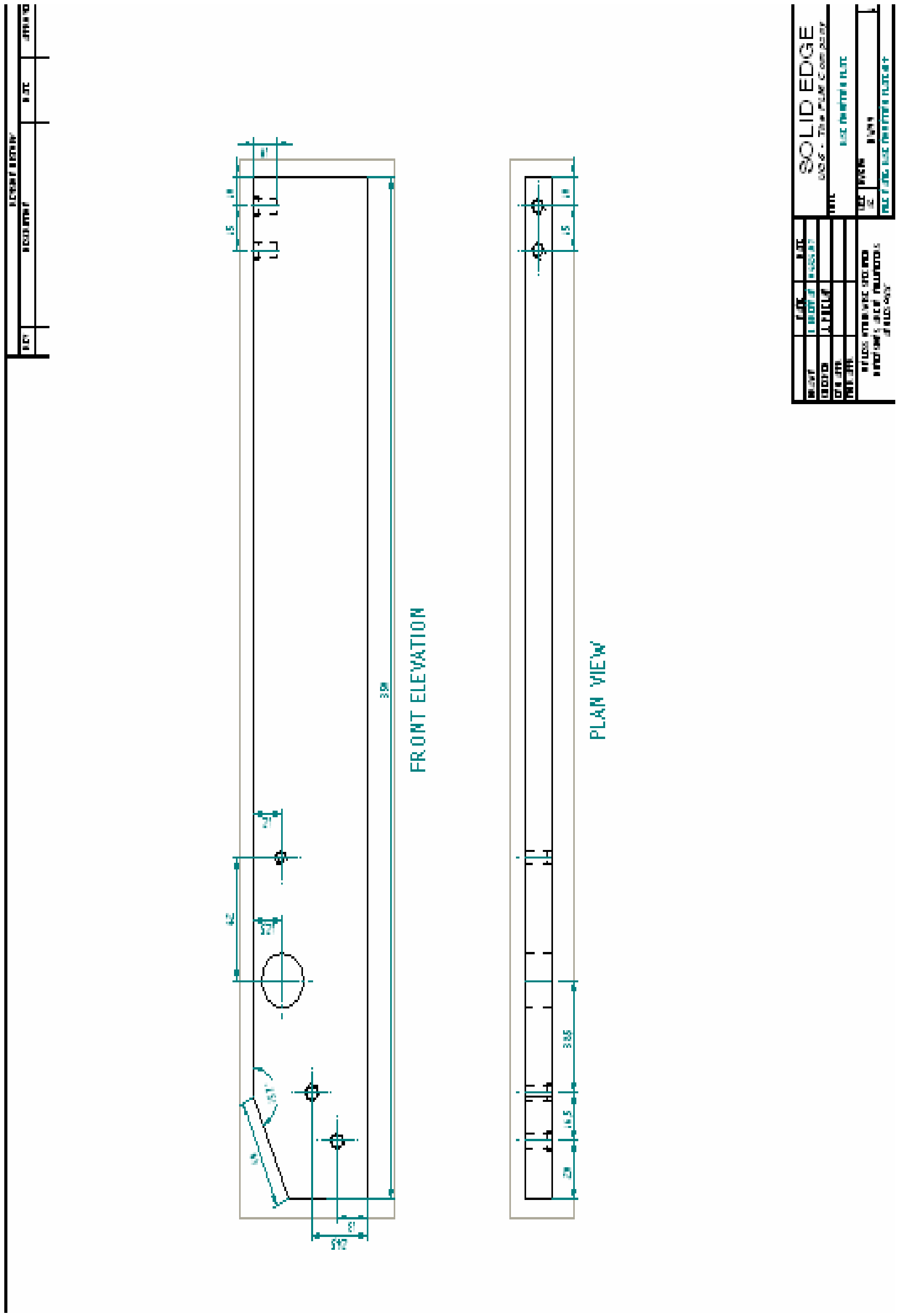
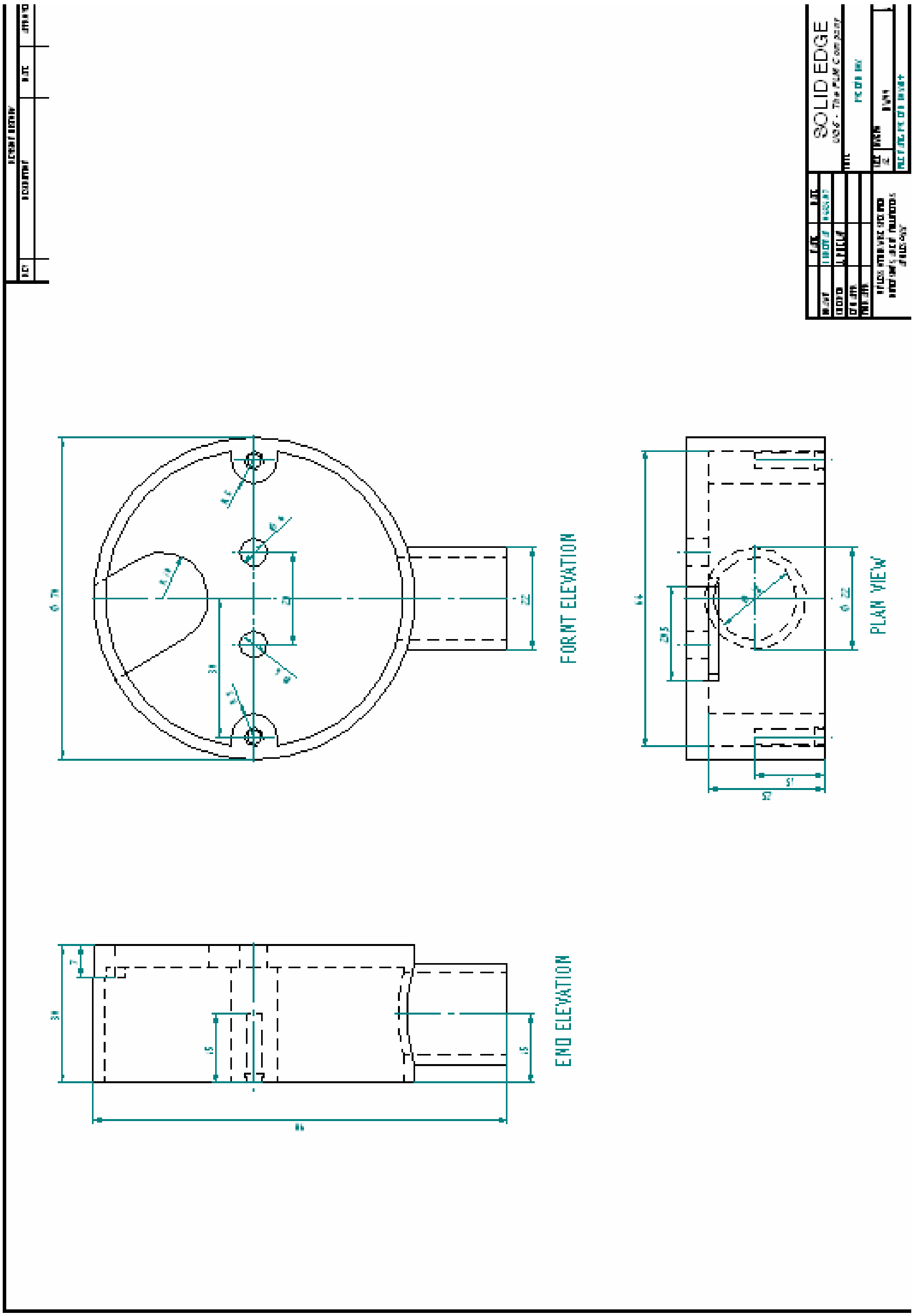
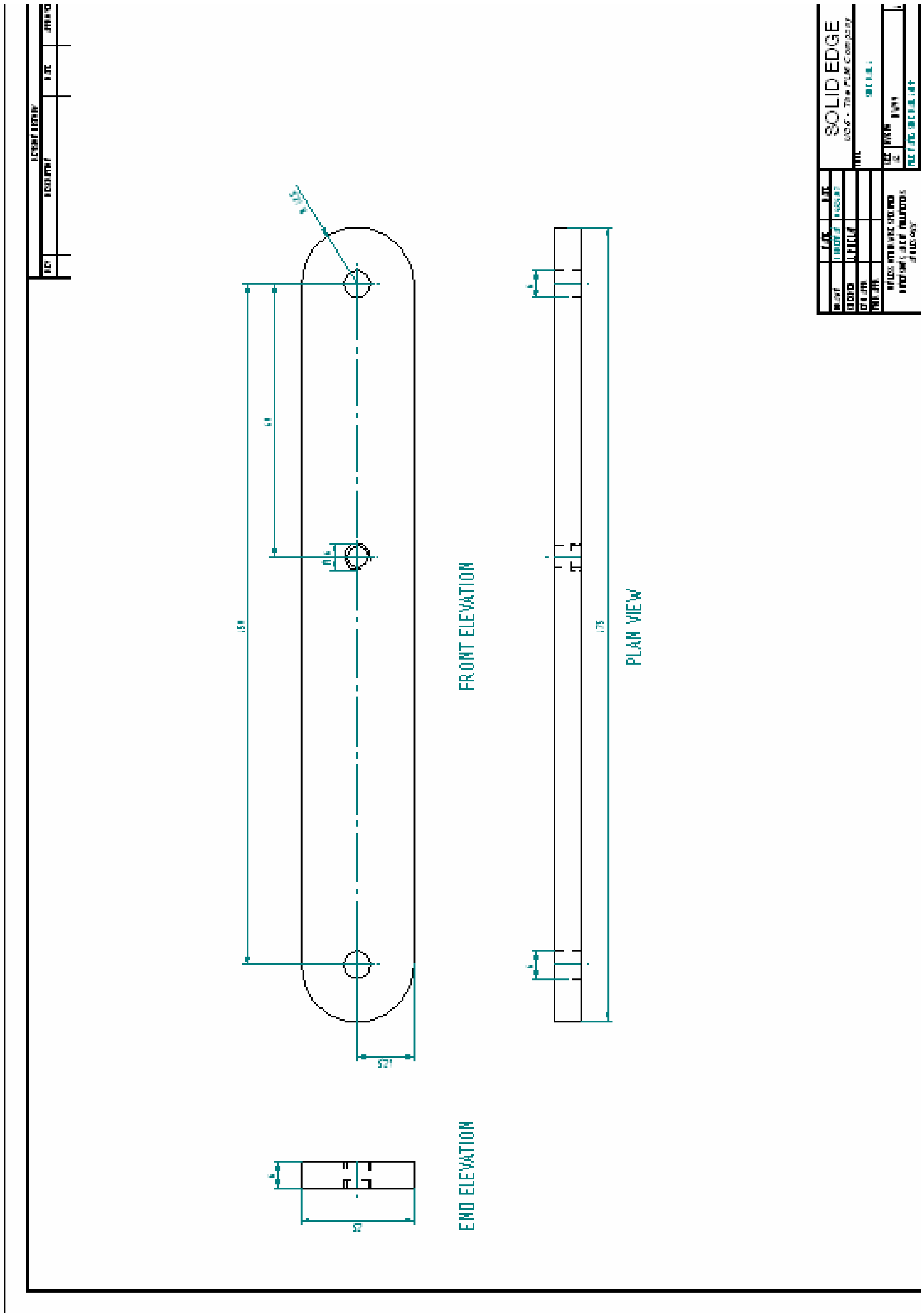
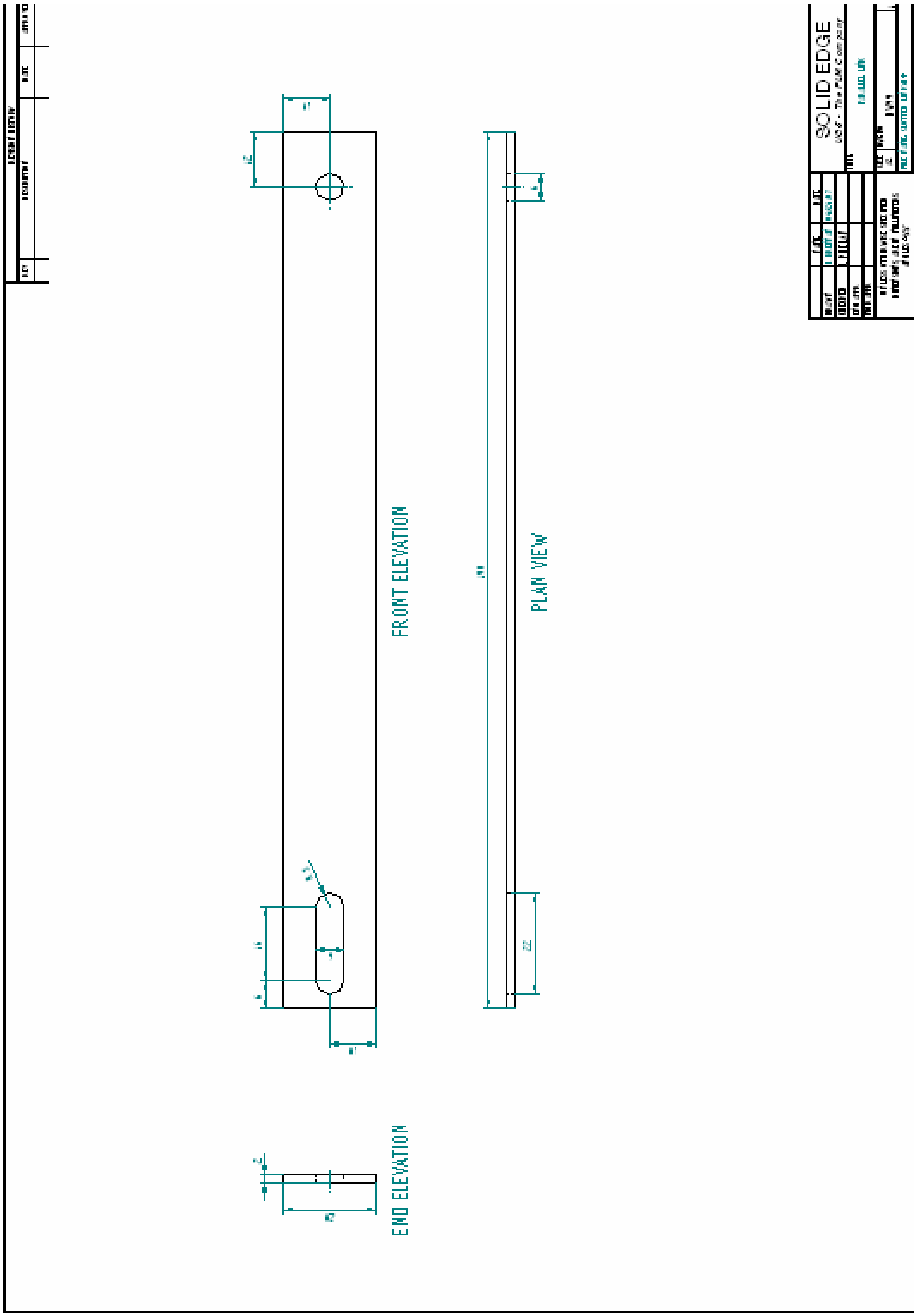

SOLID EDGE
UGS - The PLM Company
ISOMETRIC VIEW


FRONT ELEVATION
PLAN VIEW
SOLID EDGE


FORNT ELEVATION
PLAN VIEW
END ELEVATION
SOLID EDGE


SOLID EDGE
FRONT ELEVATION
PLAN VIEW
END ELEVATION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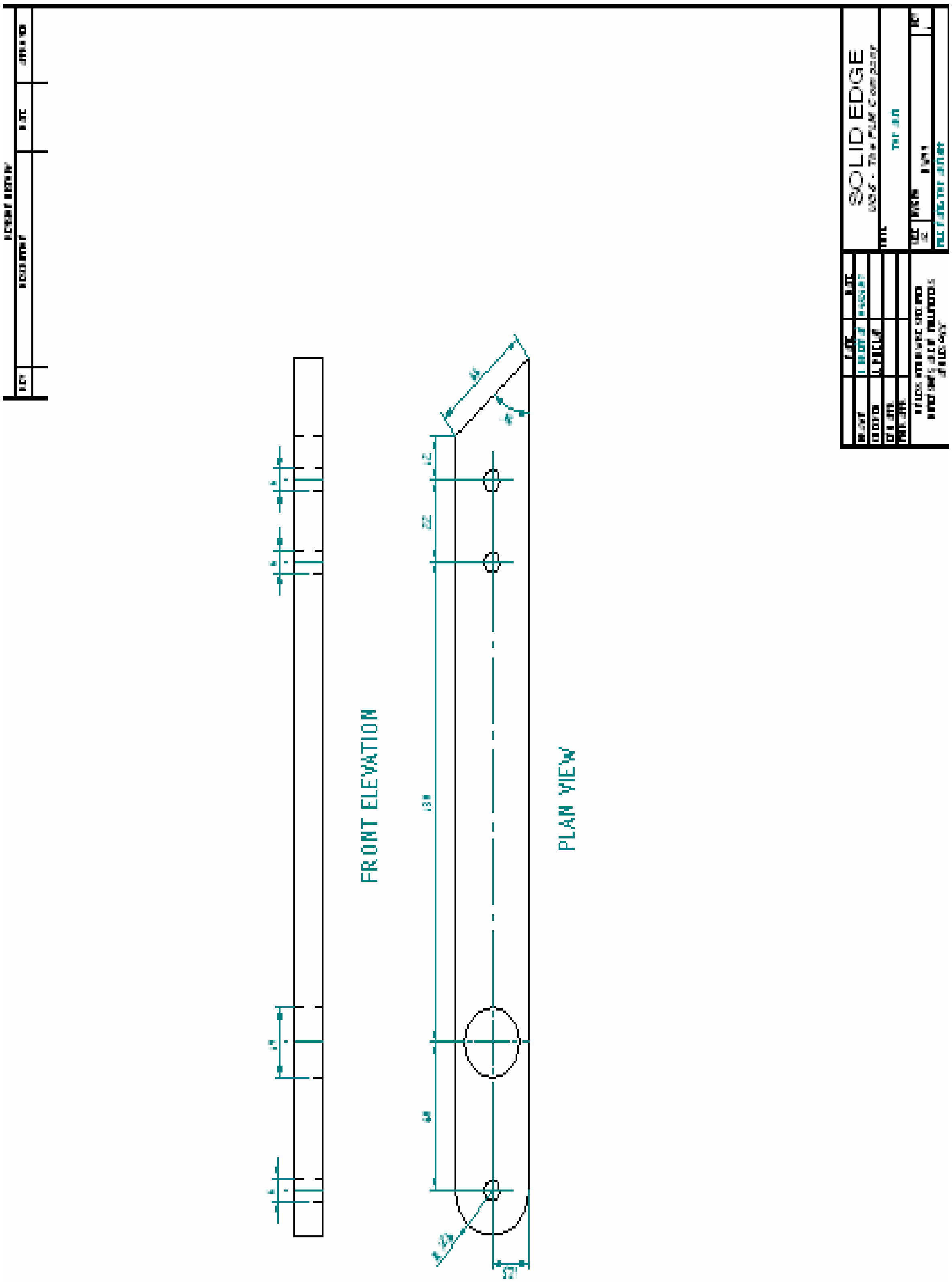
PLAN VIEW
END ELEVATION
SOLID EDGE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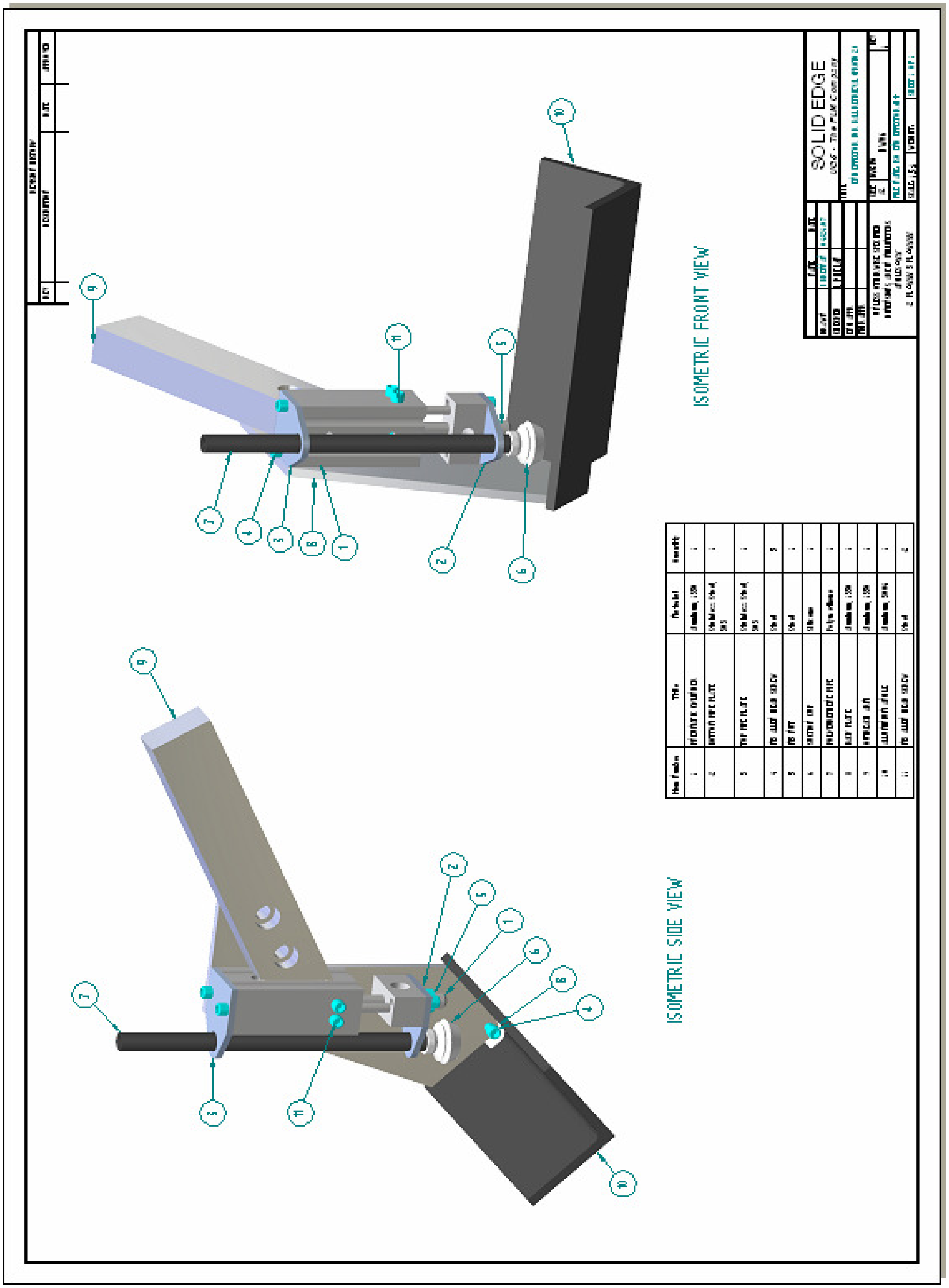
PLAN VIEW
SOLID EDGE

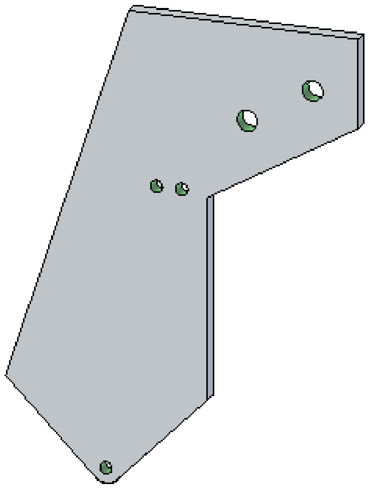
12 Appendix B (CAD drawings of end effecter Prototype#1)



Appendix

Main components of suction cup end effecter.

1. Back plate
2. Outreach arm
3. Suction pipe
4. Suction cup
5. Pneumatic cylinder



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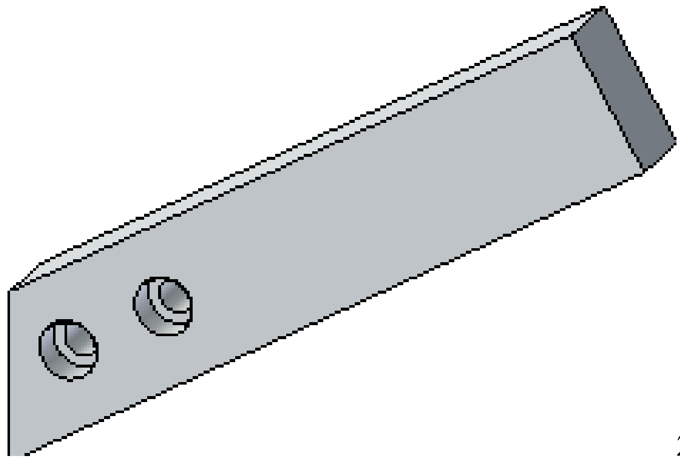

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3.

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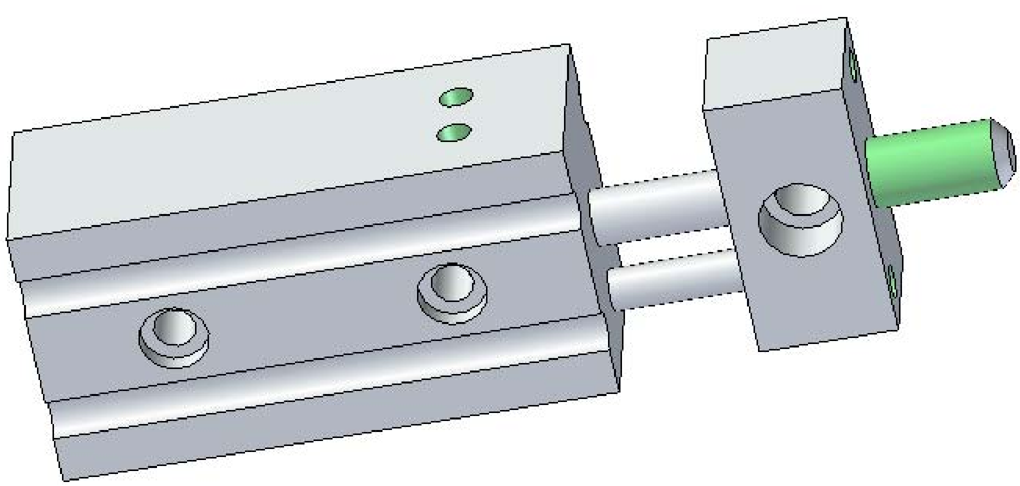

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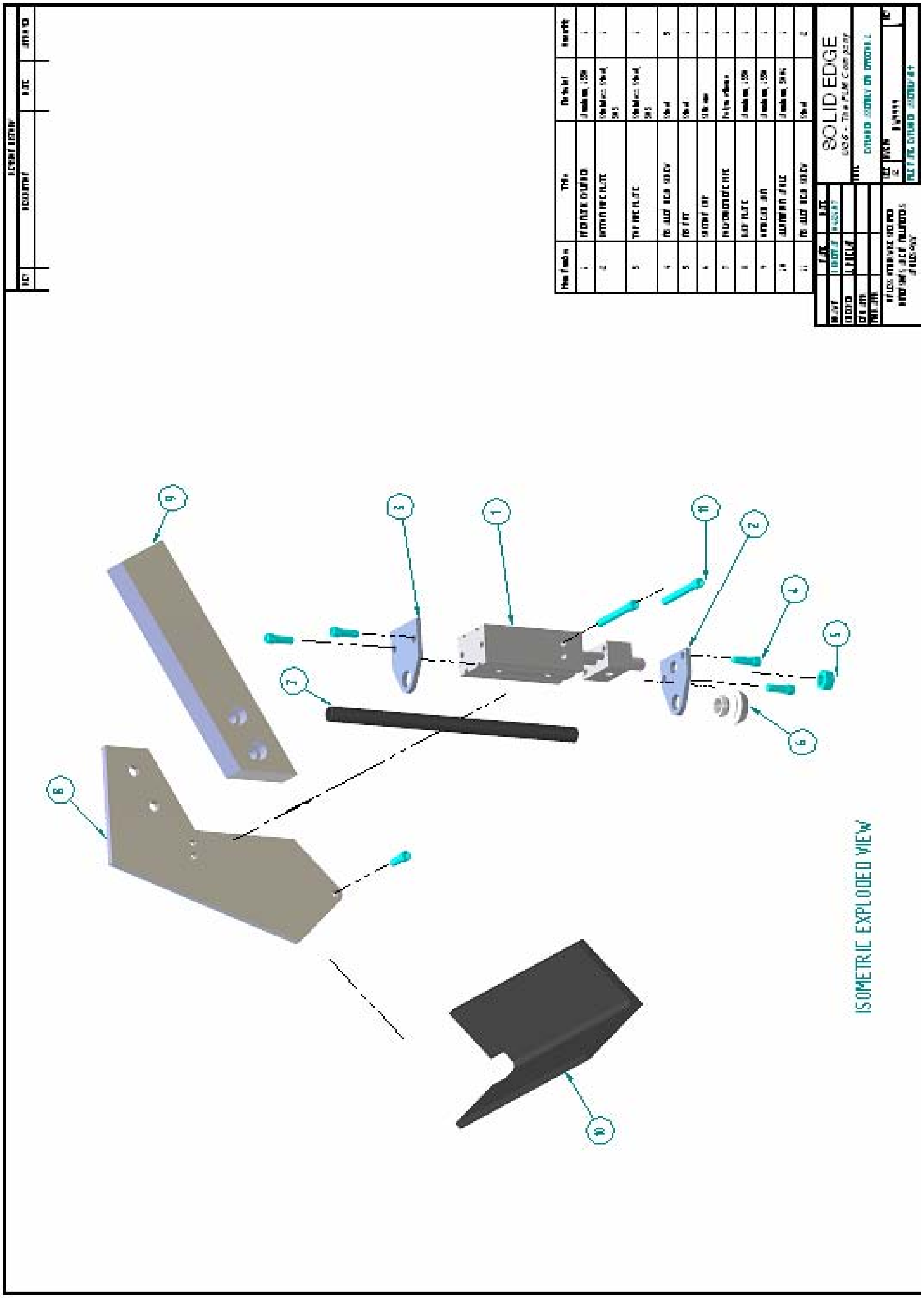
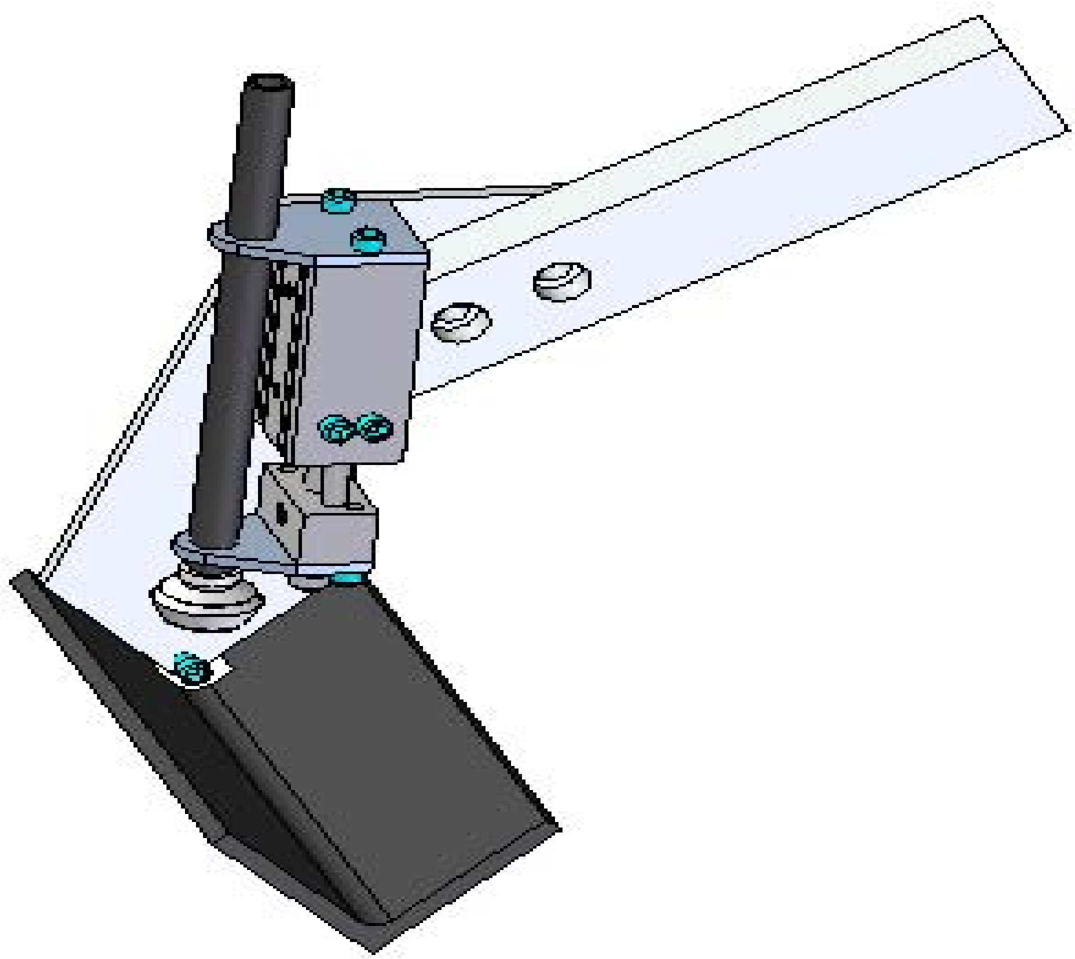
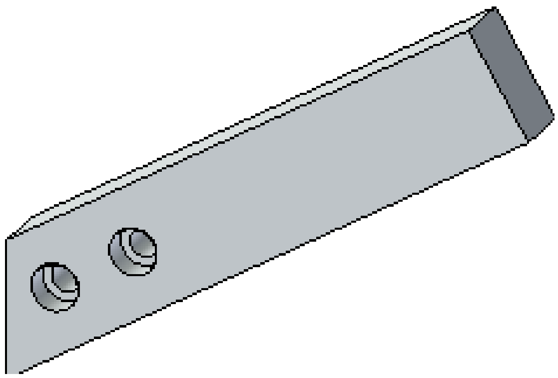

ISOMETRIC EXPLODED VIEW
SOLID EDGE

Final assembly of suction cup end effecter



13 Appendix C (CAD drawings of end effecter Prototype#2)

1. Outreach arm
2. Back plate
3. End effecter assembly with approach plate.



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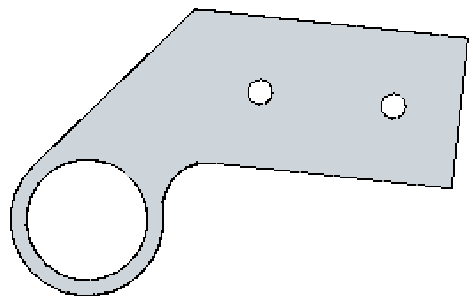

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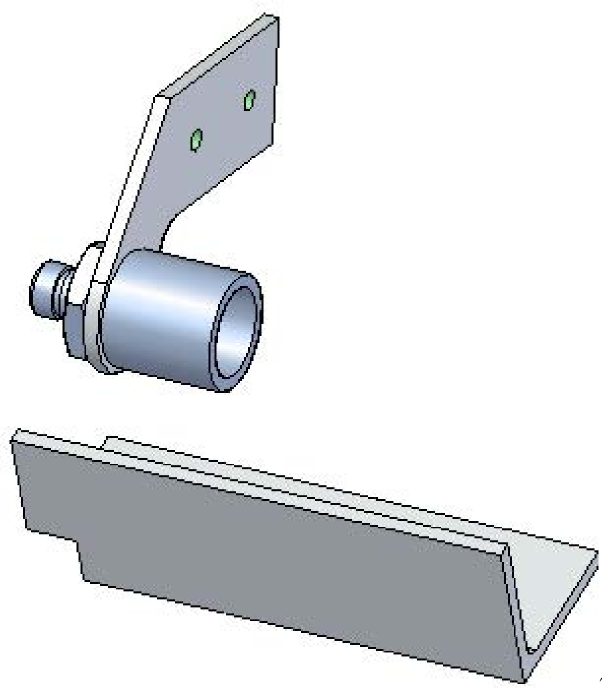

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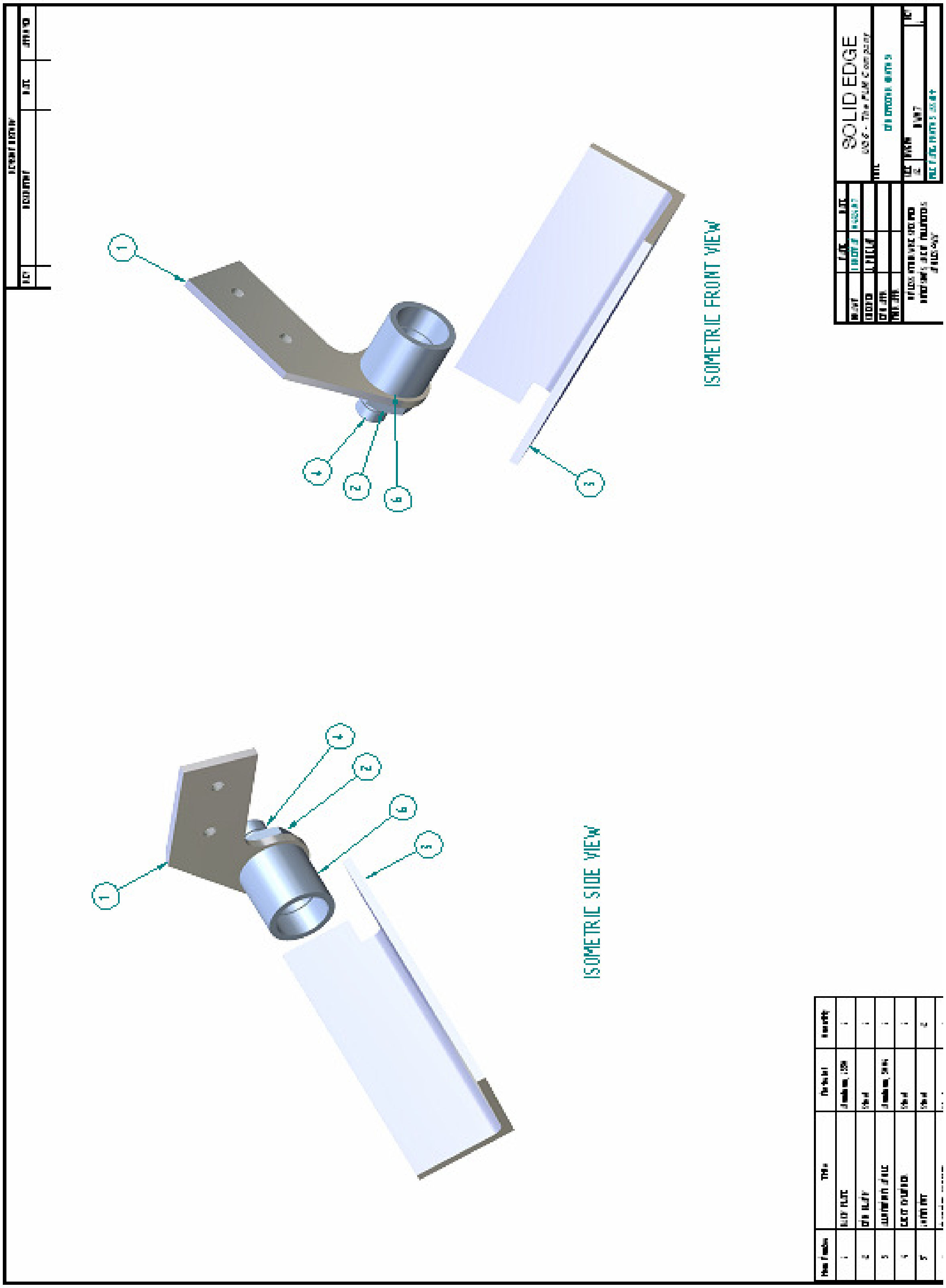
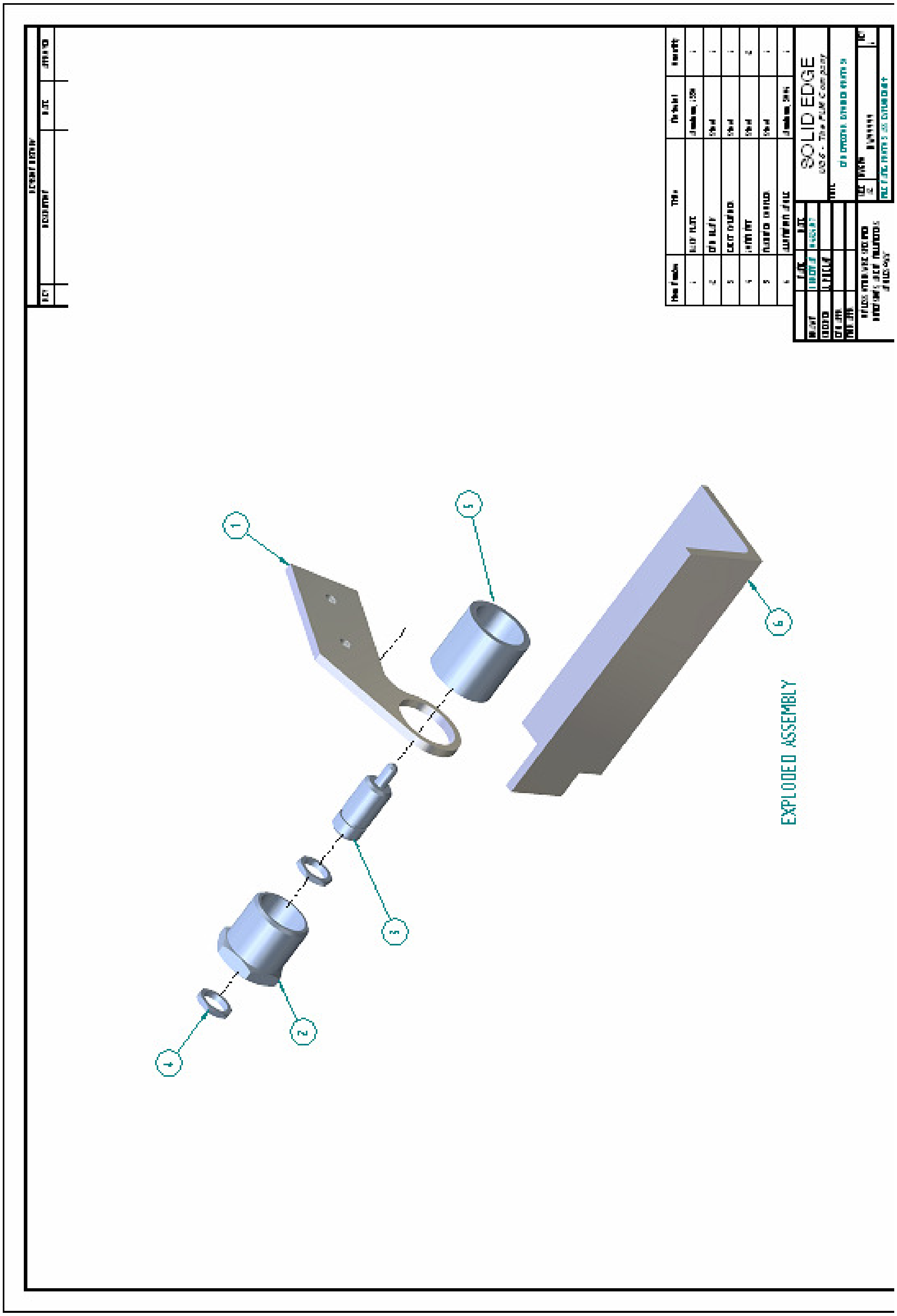
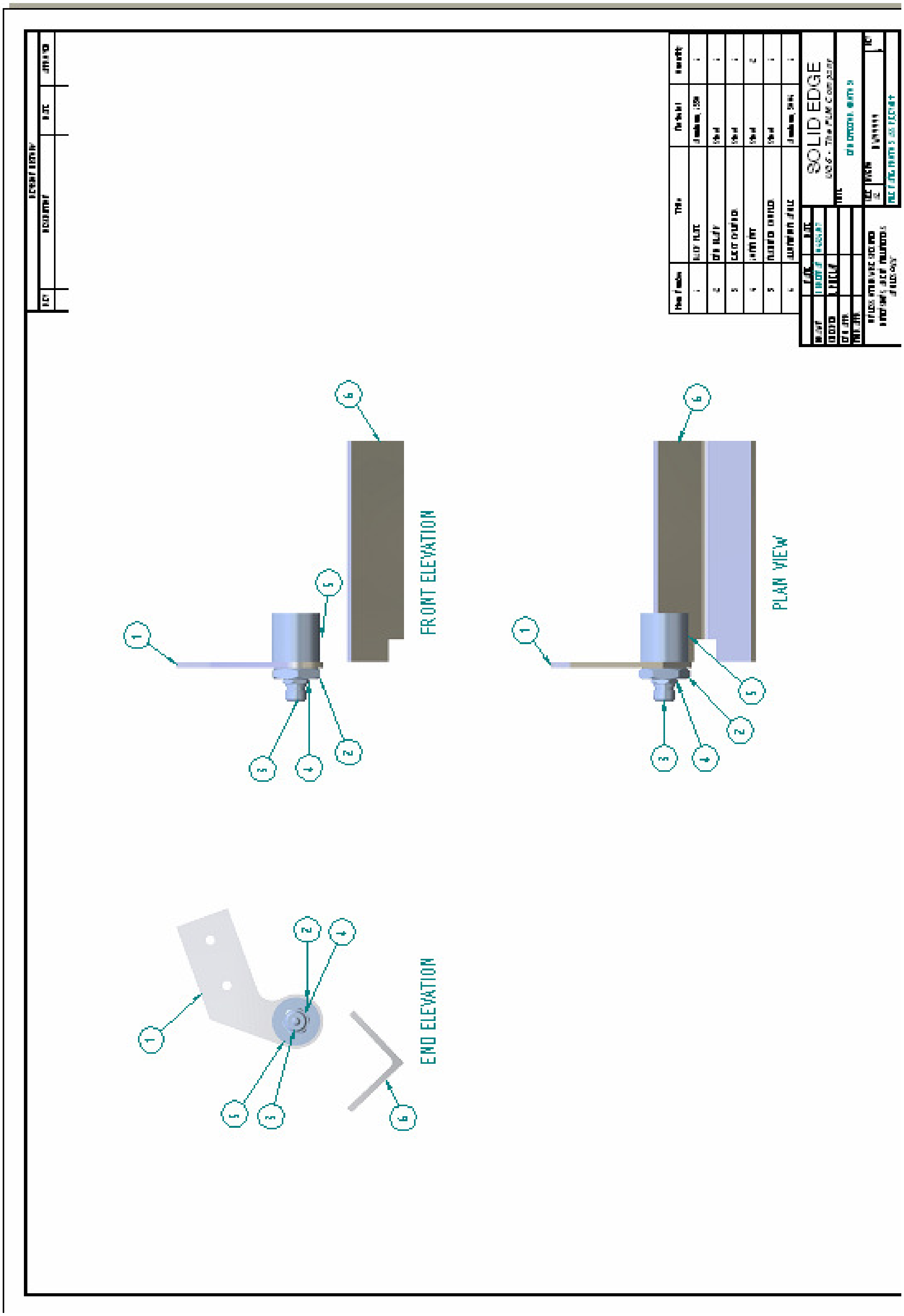
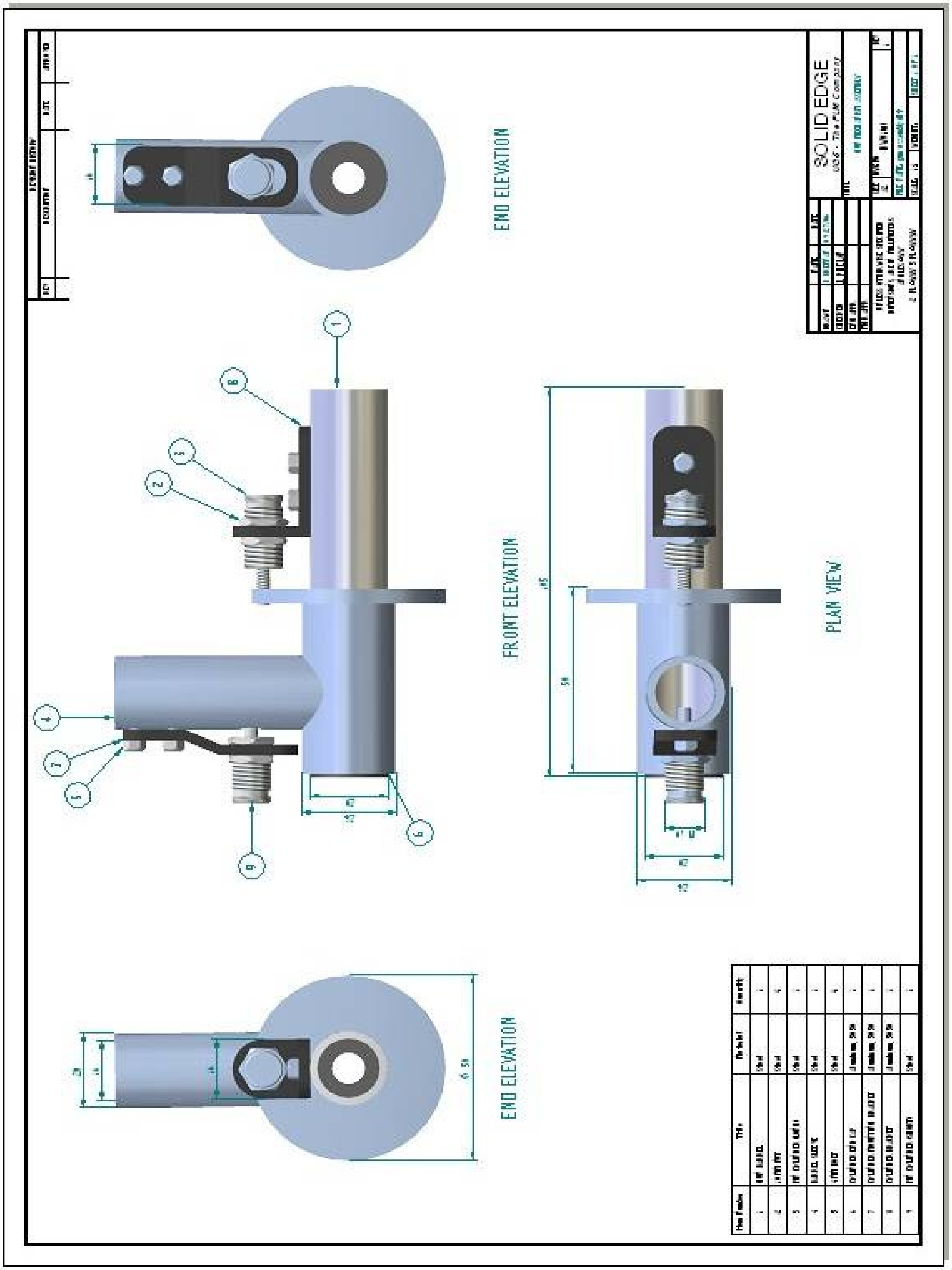
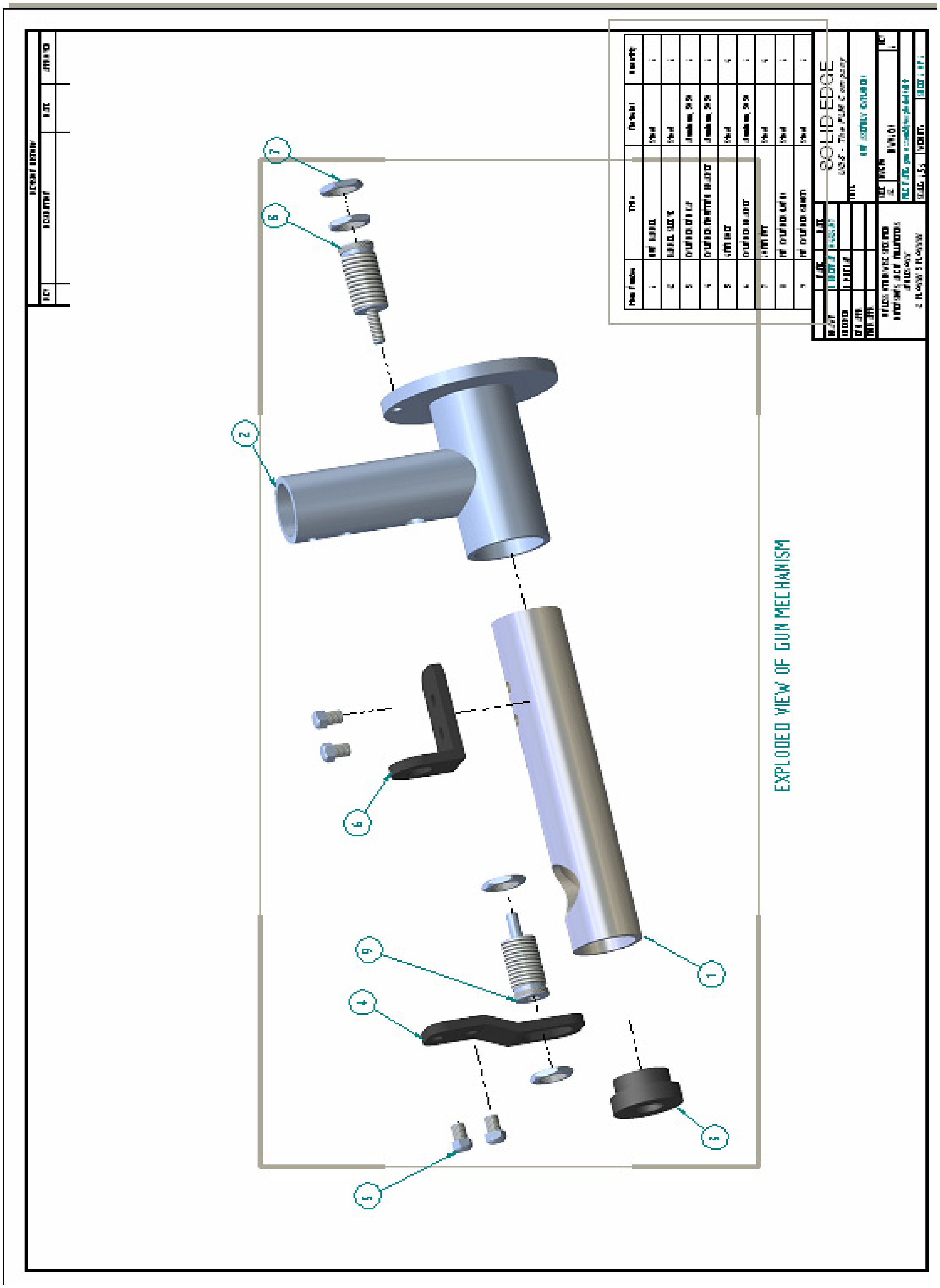

ISOMETRIC FRONT VIEW
ISOMETRIC SIDE VIEW
SOLID EDGE
1
2
3
4
6


EXPLODED ASSEMBLY
SOLID EDGE

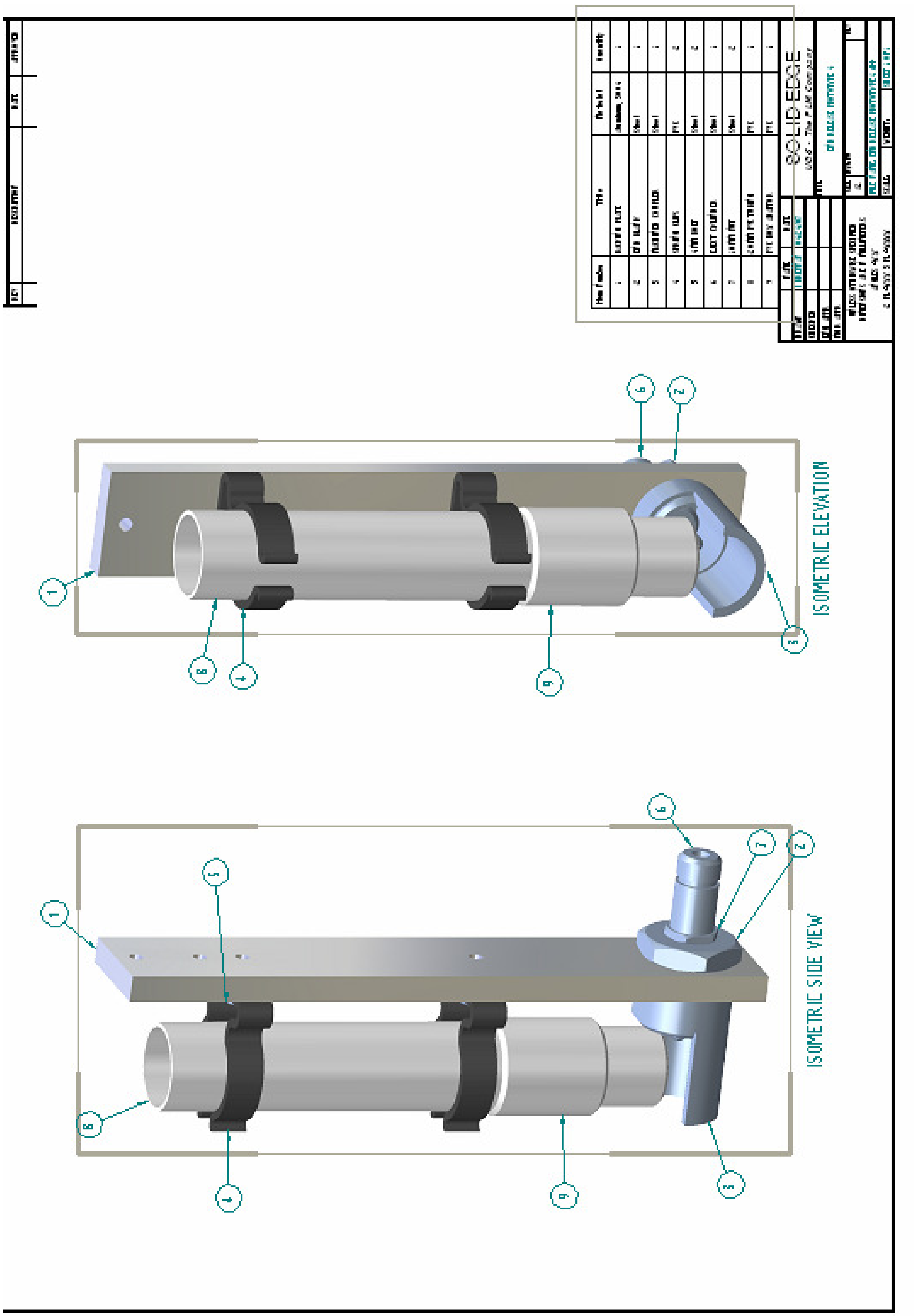

FRONT ELEVATION
PLAN VIEW
END ELEVATION
SOLID EDGE

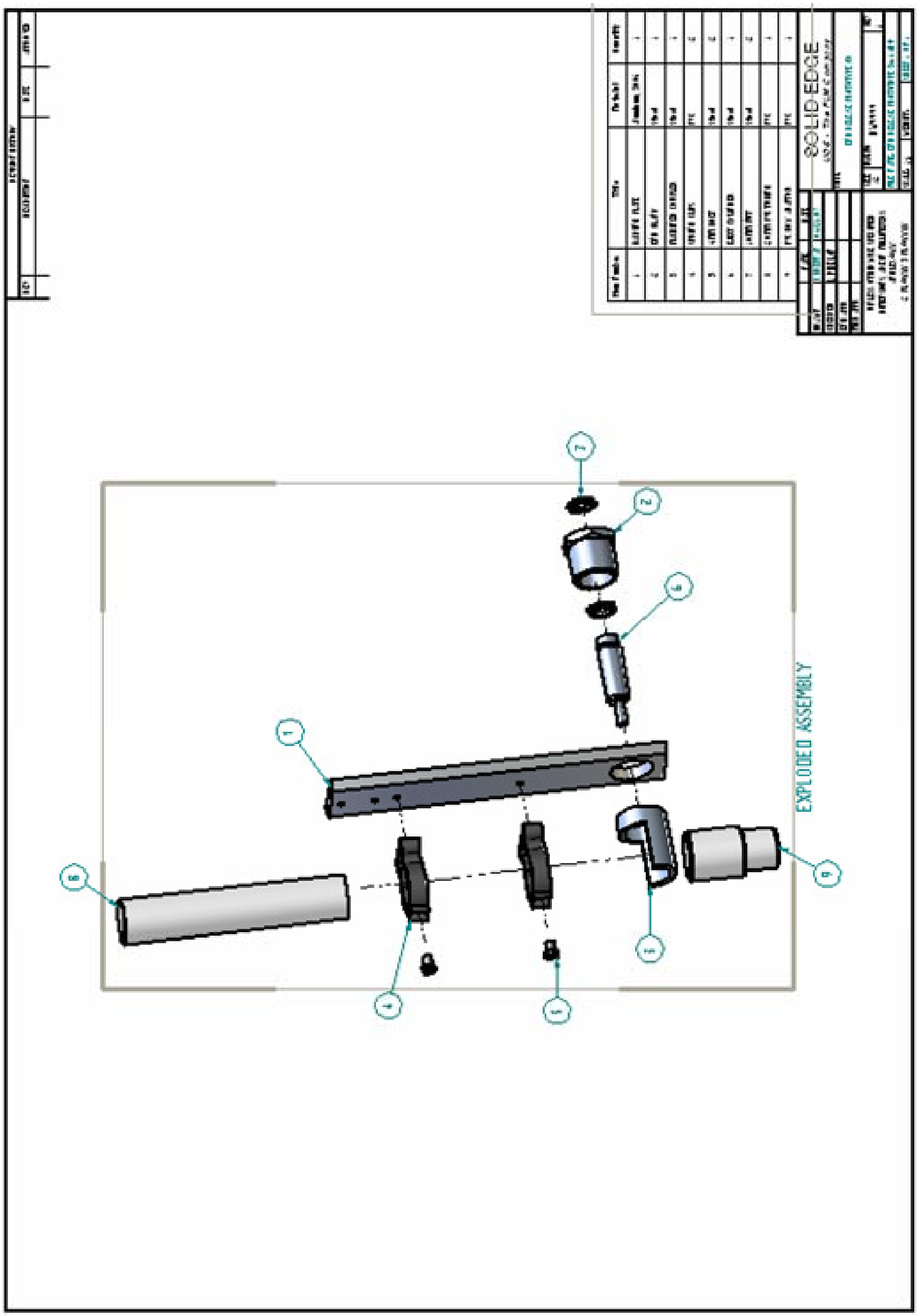
14 Appendix D (CAD drawings of Air Gun Prototype#1)



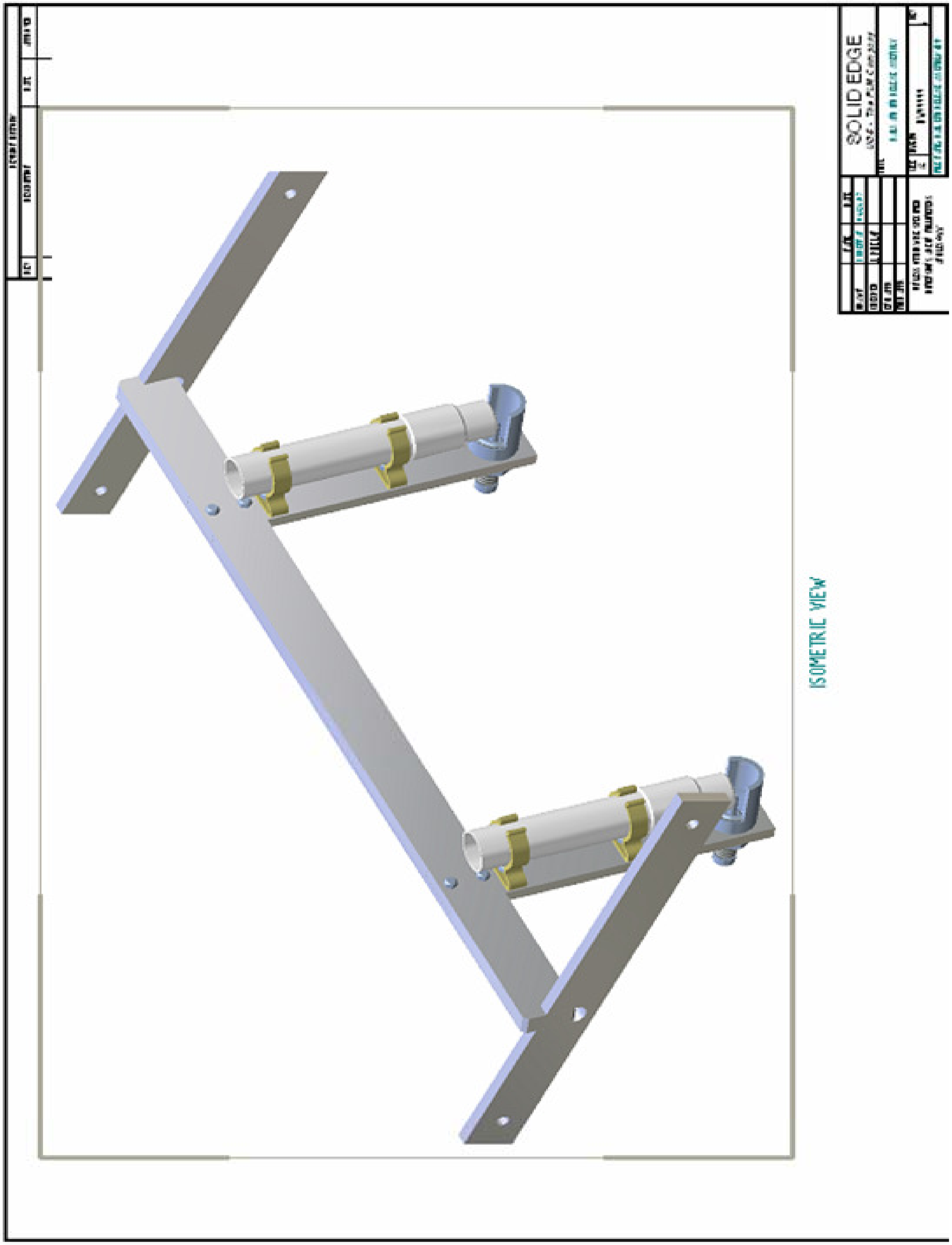

EXPLODED VIEW OF GUN MECHANISM
SOLID EDGE

15 Appendix E (CAD drawings of Ball release system)

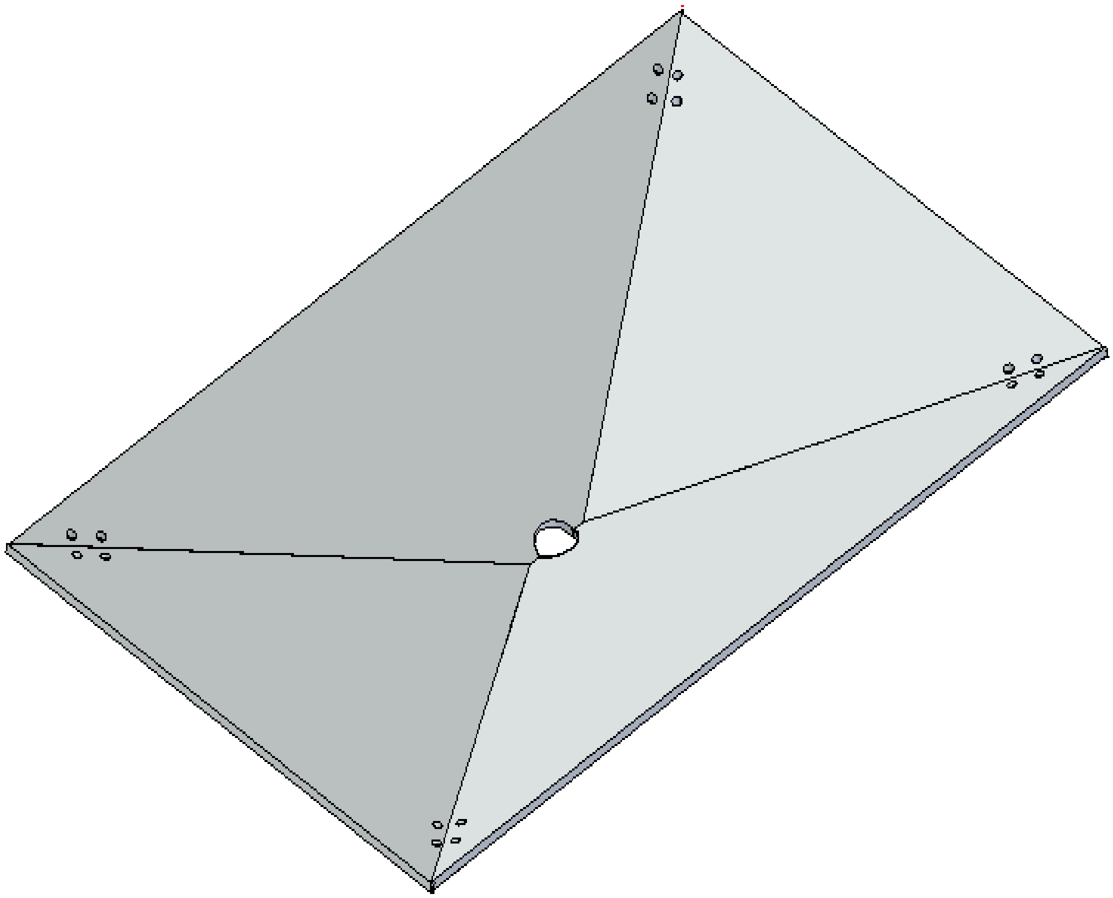



EXPLODED ASSEMBLY
SOLID EDGE

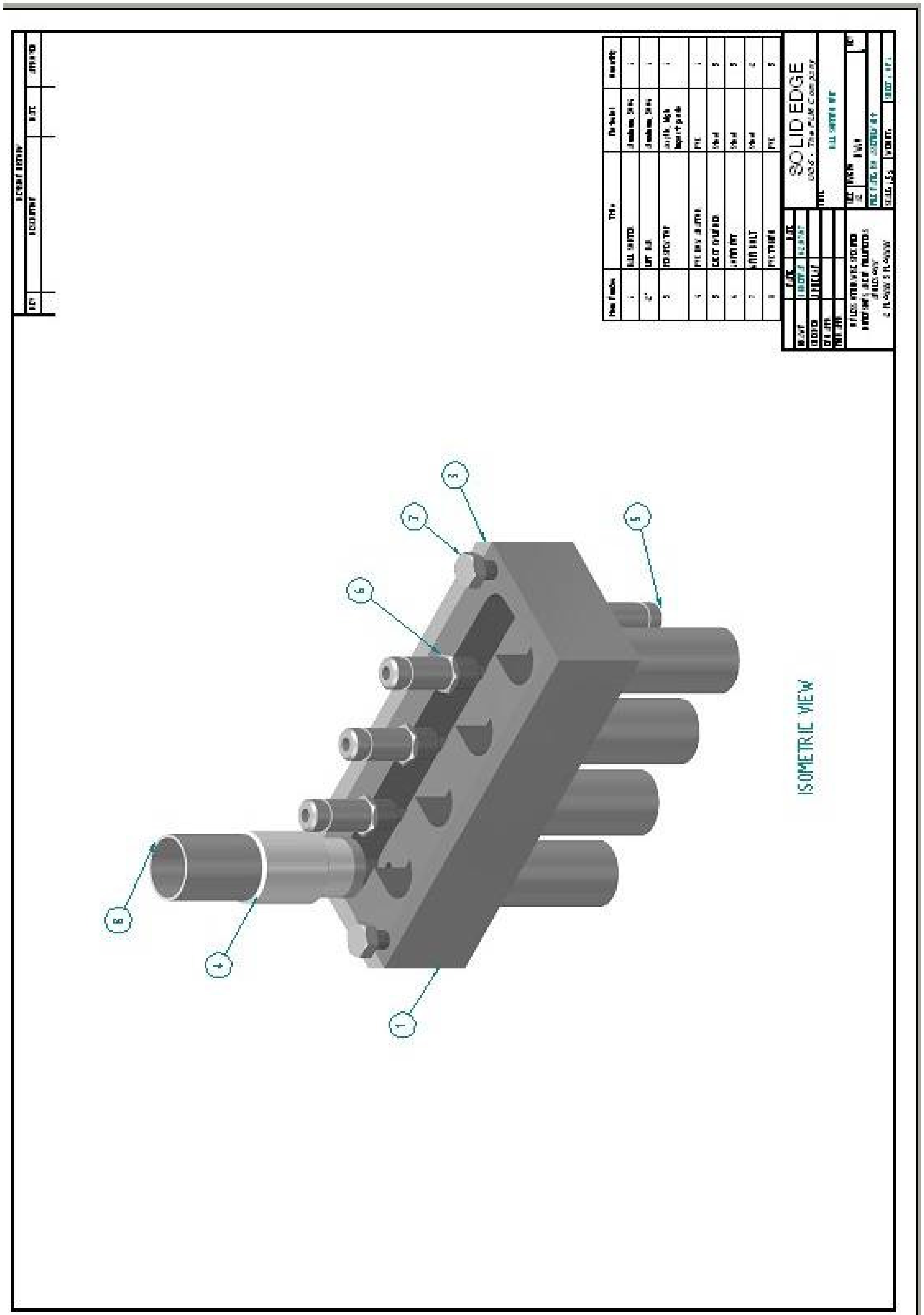
16 Appendix F (CAD drawings of Release system bracket)



Inverter Pyramid Funnel



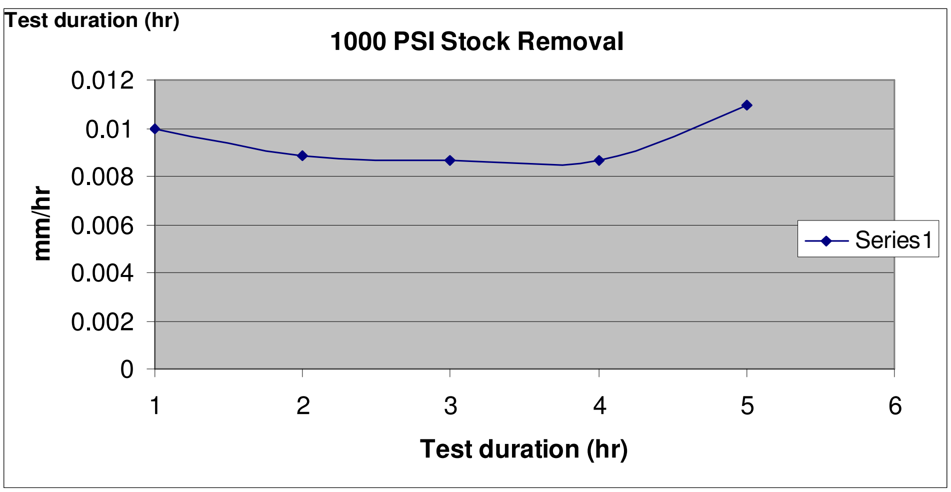
17 Appendix G (Calibration ball sorting system)

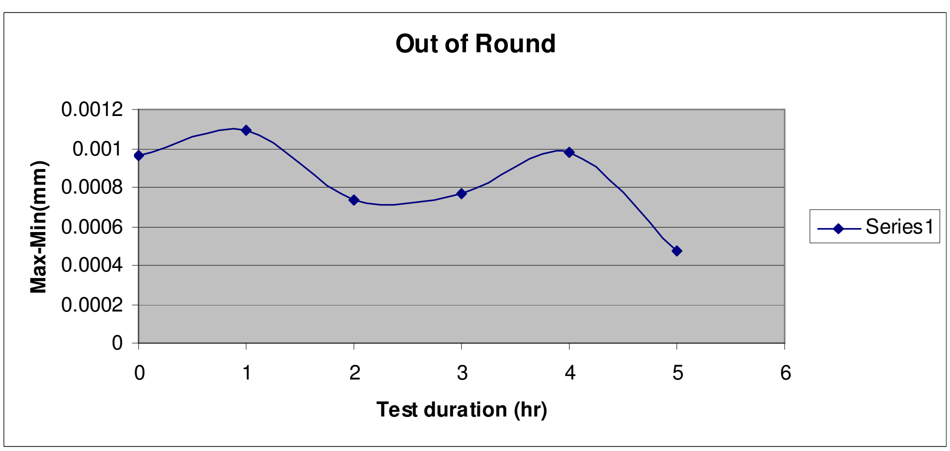


18 Appendix H (Stock removal versus pressure results)

Stock removal test results at 1000p.s.i

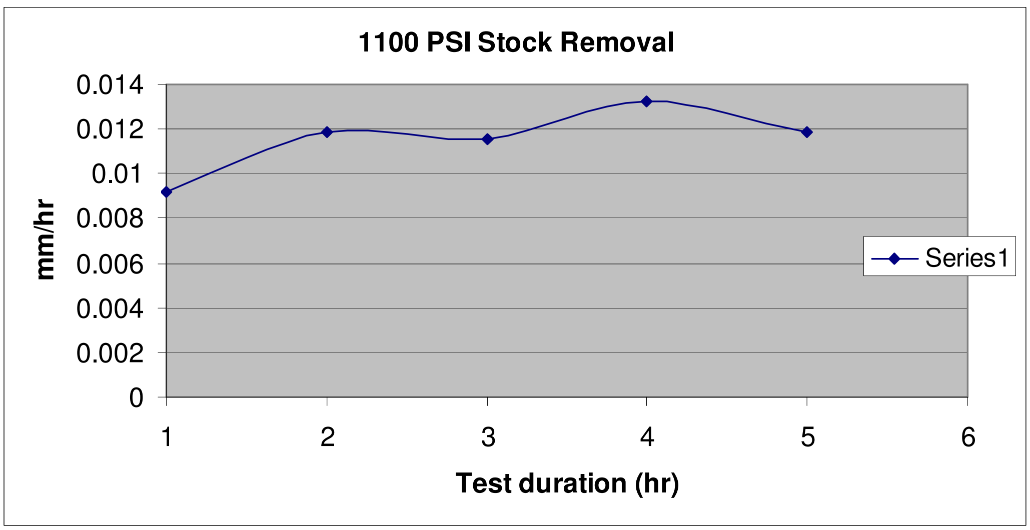
Test duration (hr)	STOCK REMOVED mm/Hr	Out of Round (Max-Min)	Actual Out of Round	
0	0	0.0009652	Stastics	micron
1	0.00994664	0.00109728	Average	2.38000
2	0.00887984	0.00073152	Range	0.88500
3	0.0086741	0.00076708	Max	1.93600
4	0.00867156	0.00098044	Min	2.82000
5	0.010922	0.00047244	Cp	341.76800
AVERAGE	0.009418828	0.00083566	Cpk	3.25400

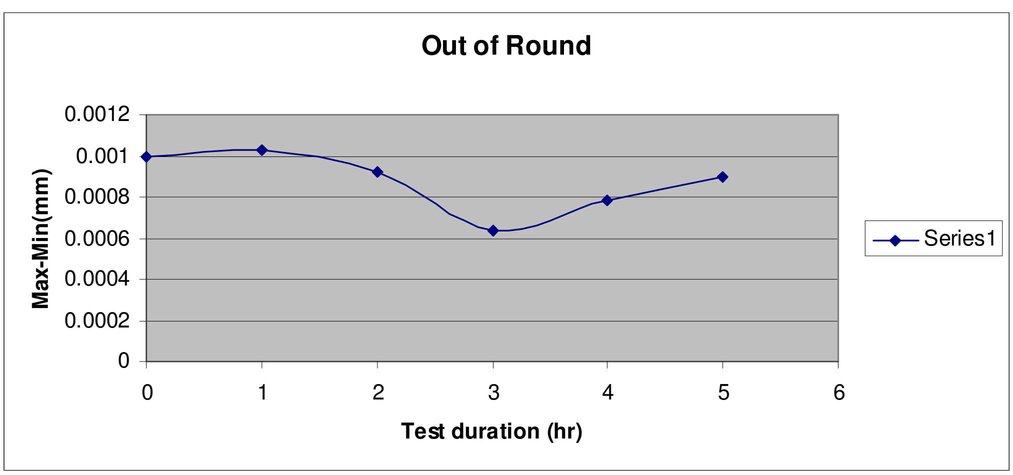




Stock removal test results at 1100p.s.i

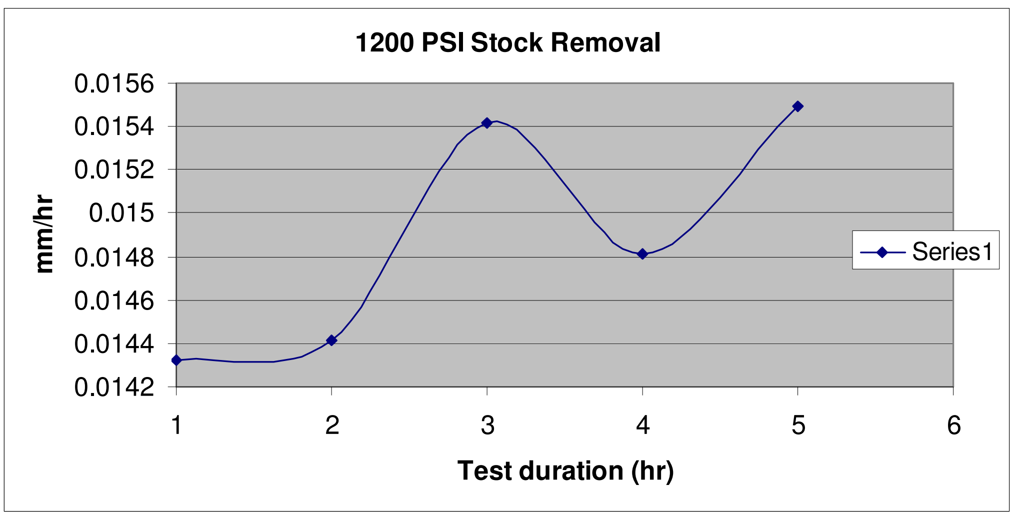
Test duration (hr)	STOCK REMOVED mm/Hr	Out of Round (Max-Min)	Actual Out of Round	
0	0	0.00099314	**Stastics**	**micron**
1	0.00915543	0.00102616	Average	3.05400
2	0.01185418	0.00091948	Range	0.97800
3	0.01157986	0.00064008	Max	2.57400
4	0.01319784	0.00078232	Min	3.55200
5	0.01184402	0.00089916	Cp	230.33100
Average	0.011526266	0.000876723	Cpk	2.81300

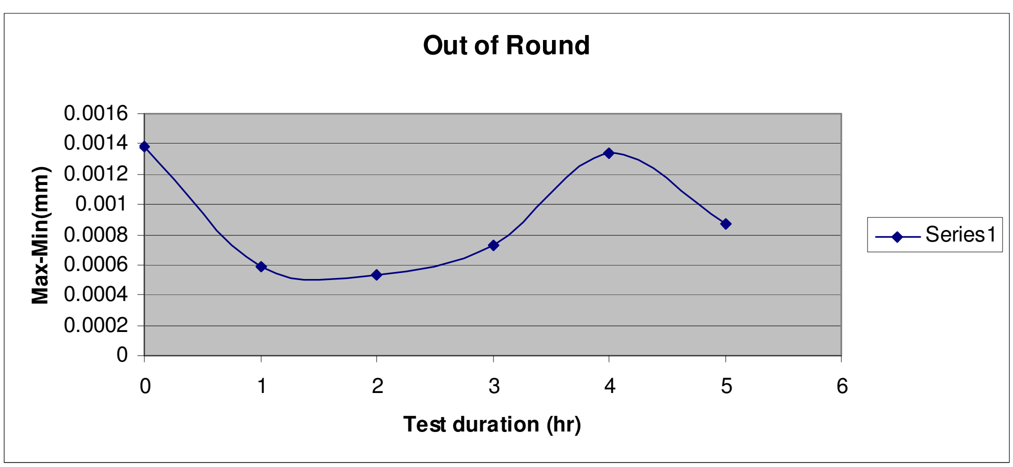




Stock removal test results at 1300p.s.i

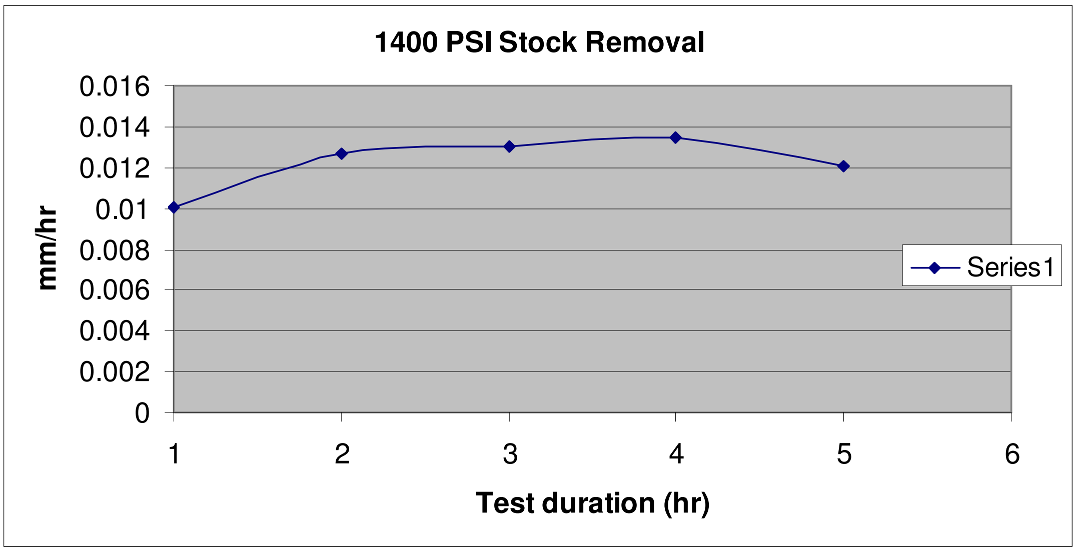
Test duration (hr)	STOCK REMOVED mm/Hr	Out of Round (Max-Min)	Actual Out of Round	
0	0	0.00138684	**Stastics**	**micron**
1	**0.01432306**	0.00058928	Average	3.58700
2	**0.0144145**	0.0005334	Range	2.01100
3	**0.01541526**	0.00073152	Max	4.59800
4	**0.01481582**	0.00133604	Min	2.58700
5	**0.015494**	0.00086868	Cp	138.20100
Average	**0.014892528**	**0.000907627**	Cpk	1.98300

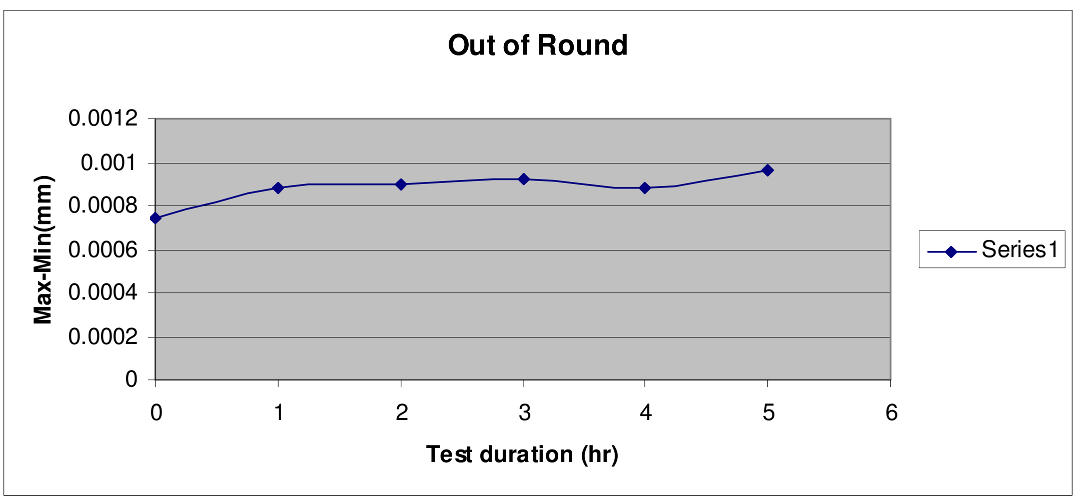




Stock removal test results at 1400p.s.i

Test duration (hr)	STOCK REMOVED mm/Hr	Out of Round (Max-Min)	Actual Out of Round	
0	0	0.00074676	**Sta+stics**	**micron**
1	0.01008126	0.00088392	Average	3.81700
2	0.0126365	0.00089916	Range	2.49400
3	0.01306322	0.00092456	Max	5.45400
4	0.01346708	0.00088392	Min	2.96000
5	0.01206246	0.00096012	Cp	111.07200
Average	0.012262104	0.000883073	Cpk	1.69600

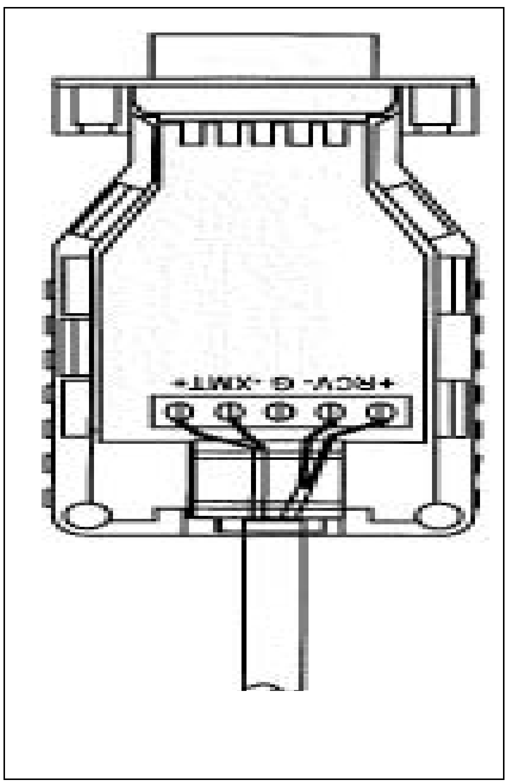




19 Appendix I (Wiring the RS232/422 Converter)

The cable being used to transfer the data is a Category 5 Ethernet Cable. Within this cable there are four twisted pairs and an earth. For bi-directional data transfer using this converter, only two of the twisted pairs and the earth are required. As shown in the diagram below, the RS232/RS422 converter has 5 terminals; transmit positive and negative, and receive positive and negative.

Firstly the RS232/RS422 converter at the central controller is wired with the two twisted pairs and the ground. The converter on the device side is then wired in the opposite way to the converter on the central controller side. Ultimately, a two pair cross over connection needs to be constructed as shown below in the wiring instructions.

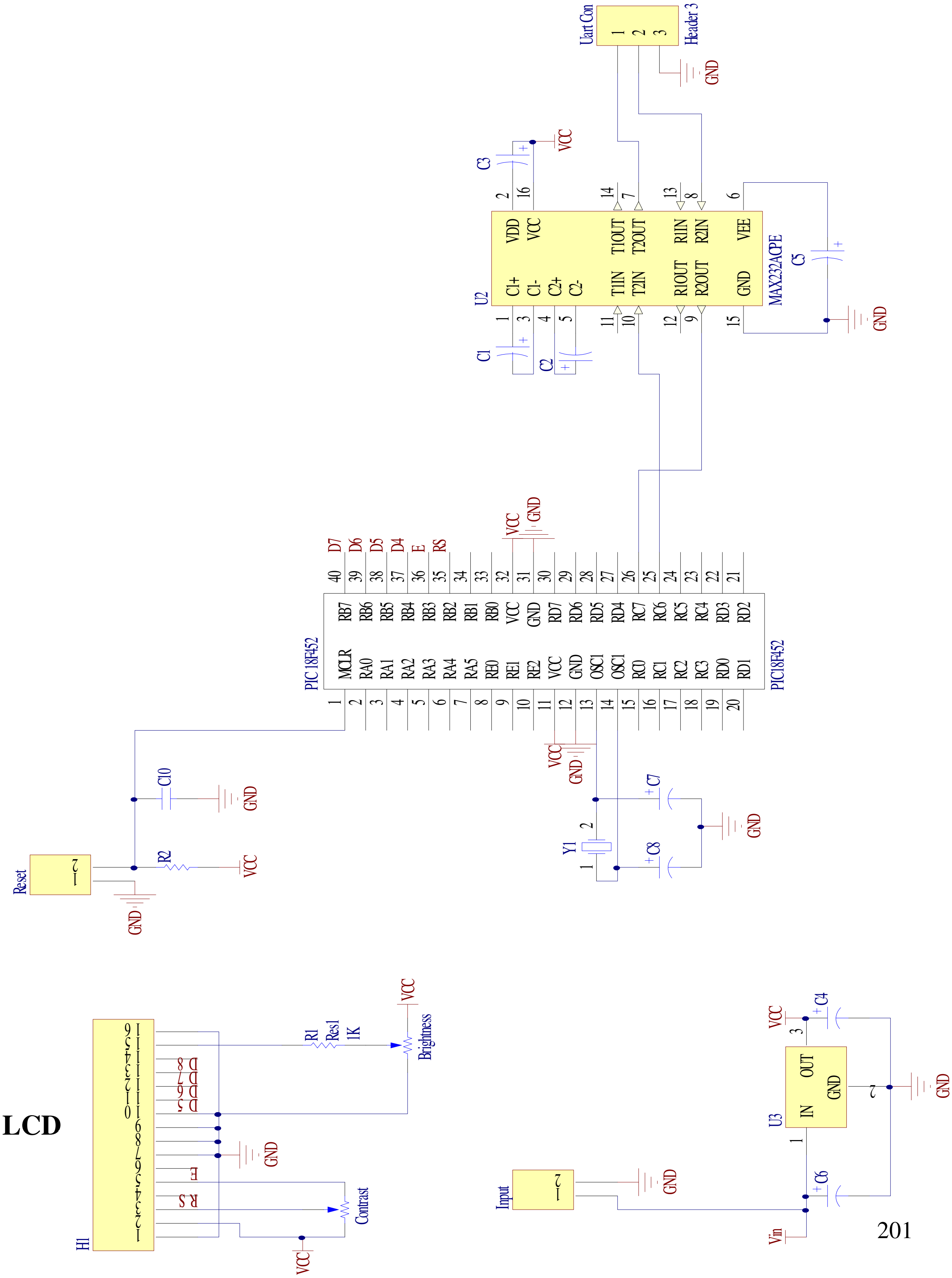


<u>Converter Wiring Instructions</u>

Central Controller Converter	**Device Converter**
XMT+………………RCV +	
XMT -………………RCV –	
GND………………...GND	
RCV +……………….XMT +	
RCV -……………….XMT -	

20 Appendix J (PCB board Layout)

The schematic and PCB layout for the measurement display board.



21 Appendix K (development of control chart)

- STEP #1 - Collect the data.

- STEP #2 - Divide the data into sub groups. The number of samples is represented by the letter “n” and the number of subgroups is represented by the letter "k". The data should be divided into subgroups in keeping with the following conditions.

- STEP #3 - Record the data on a data sheet. Design the sheet so that it is easy to compute the values of X bar each sub group

- STEP #4 - Find the mean value (Xbar). Use the following formula for each sample where Xbar (the mean of the sample) is the sum of the results divided by N (the number of balls).

$$\text{Xbar} = \frac{X1 + X2 + X3 + X4 + X5....}{N}$$

- STEP #5 - Find the overall mean, or X double bar $\bar{\bar{X}}$. X double bar is the sum of sample means divided by the K (the number of samples).

$$\text{X double bar} = \frac{N1 + N2 + N3 + N4 + N5....}{K}$$

- STEP #6 - Compute the Control Limit Lines using the following formula where σ = standard deviation.

  Xbar Control Chart:

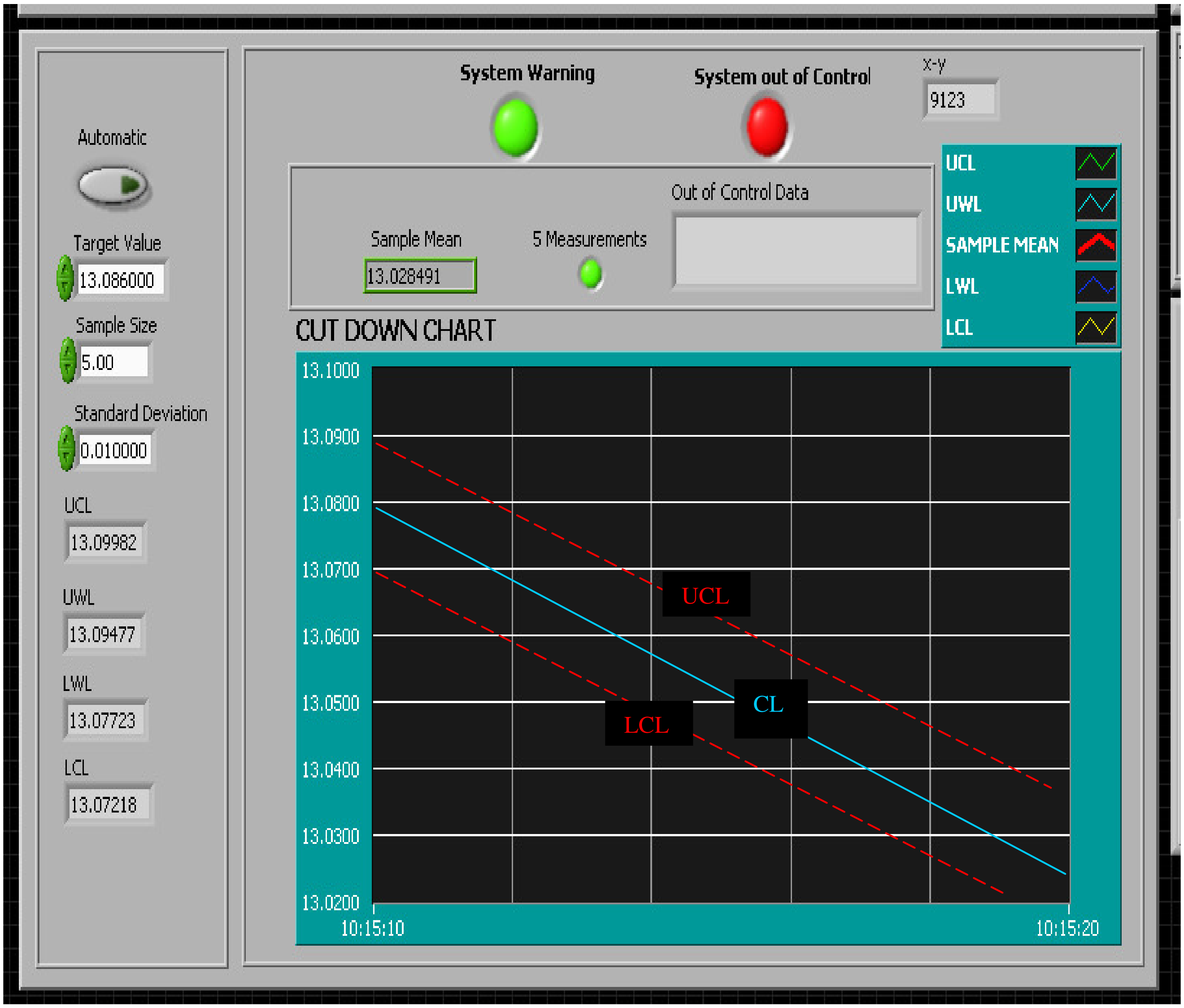
  Central Line (CL) = X double bar figure you calculated.

  Upper Control Limit (UCL) = $\overline{X} + 3.09\sigma$

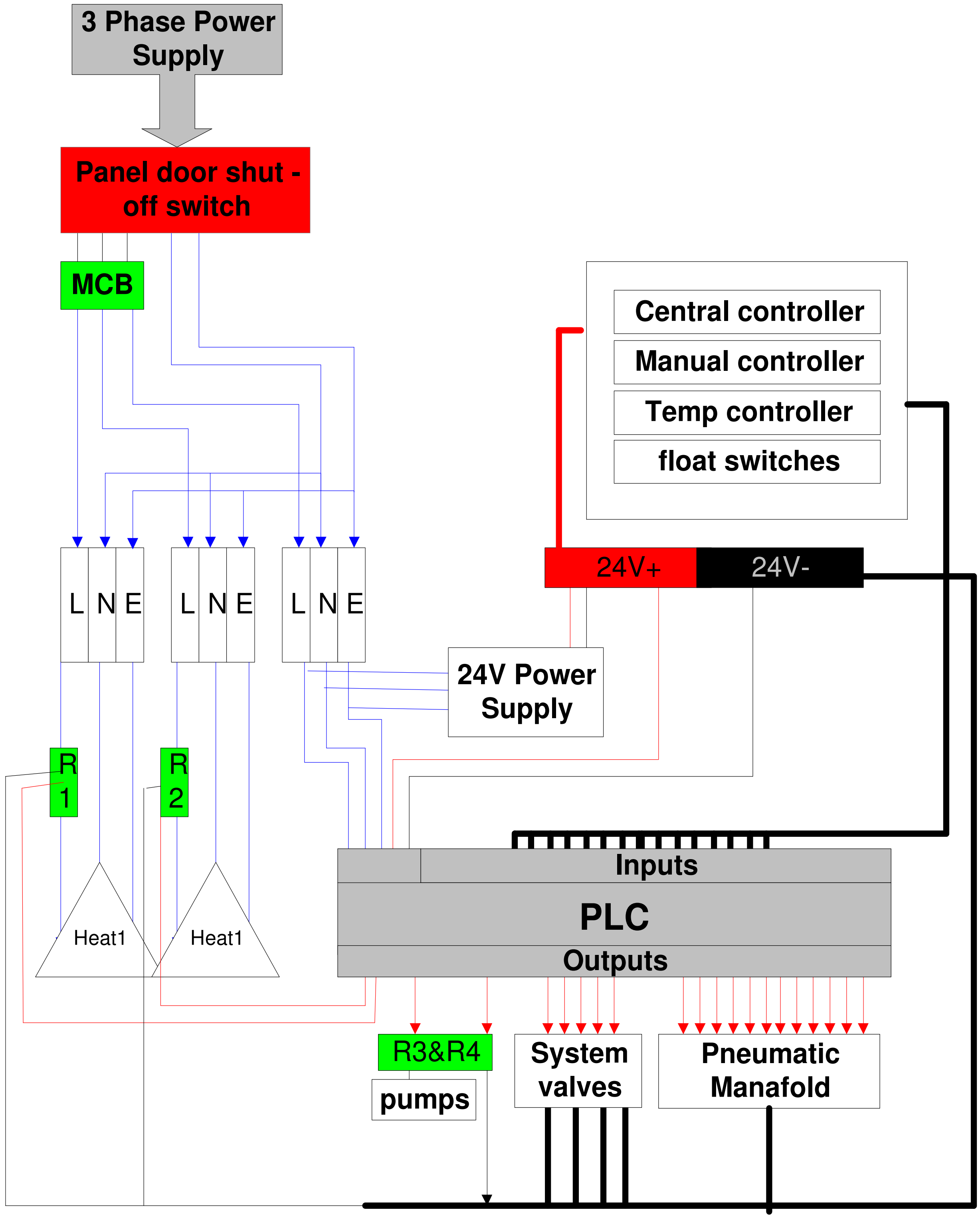
  Lower Control Limit (LCL) = $\overline{X} - 3.09\sigma$

- STEP #7 - Construct the Control Chart. Draw in the Control lines CL, UCL and LCL, and label them with their appropriate numerical values. The Upper and Lower control limits are usually drawn as broken lines.

<u>Screen shot of the constructed cut-down control chart for the 13mm Balls</u>



22 Appendix L (Schematic of Pilot Plant [28] and Grinding m/c electrical control Panels)



23 Appendix M (Project PLC Programs)