Development of Control System to Automate the PCB Pin Insertion Process

by

Rejin Isaac

B.Tech., National Institute of Technology Karnataka (2010)

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

Master of Engineering in Manufacturing

at the

MASSACHUSETTS INSTITUTE OF TECHNOLOGY

September 2012

Author ....
Department of Mechanical Engineering
August 21, 2012

Certified by ....
David E. Hardt
Ralph E. and Eloise F. Cross Professor of Mechanical Engineering
Thesis Supervisor

Accepted by ....
David E. Hardt
Chairman, Department Committee on Graduate Studies

Development of Control System to Automate the PCB Pin Insertion Process

by

Rejin Isaac

Submitted to the Department of Mechanical Engineering
on August 21, 2012, in partial fulfillment of the
requirements for the degree of
Master of Engineering in Manufacturing

Abstract

This thesis describes the development of the control system that runs the automated pin insertion machine in a surface mount technology assembly line. The control system is divided into 2 subsystems viz. pin sorting and pin insertion. The detailed design of the control system and its components is discussed, along with the programming of the Programmable Logic Controller for both subsystems. The development of the machine vision application used to sort the right pin types is described, with an emphasis on the image processing tools used. Applicability and robustness of these tools in the context of the pin insertion machine is described. The developed application can capture images and process them in 92 ms, significantly lower than the maximum allowable time of 500 ms. The vision system could totally eliminate the incidence of a wrong pin being passed on to the insertion head. Among the right pins, 98% of the right pins in the right orientation and 100% the pins in the wrong orientation were detected.

Thesis Supervisor: David E. Hardt
Title: Ralph E. and Eloise F. Cross Professor of Mechanical Engineering

Acknowledgments

This thesis is the result of the efforts and contributions of various people to whom I would like to express my utmost gratitude and thanks.

My team mates, Daniel Cook and Michelle Chang, whose skills and hard work made this a successful project. It was a pleasure working with you.

Lennart Pitzele, our supervisor at SynQor for providing me with invaluable advice, resources and support. Under your mentorship, I have learned a lot about manufacturing automation and system design. Thank you for making this project a great learning experience.

Prof. David Hardt, our advisor for your directions, suggestions and guidance throughout this project. I'm sure your ideas, advice and experiences will be useful throughout my career.

Jennifer Craig, our writing advisor, for reviewing the progress and helping me structure this thesis.

My parents and friends, for their constant support and inspiration throughout the project, without which none of this would have been possible.

Contents

List of Figures

List of Tables

Chapter 1

Introduction

Surface Mount Technology (SMT) is a commonly used method in the electronics industry to assemble components on a printed circuit board (PCB). SMT allows both sides of the PCB to be populated with components, as opposed to traditional through-hole technology, where the leads of electronic components are inserted and soldered into holes in the PCB, which prevents the opposite side of the PCB from being used to mount components. With SMT, the PCB can then be physically smaller than PCBs produced through traditional through-hole methods. These advantages have led to SMT being adopted as the standard assembly method in the electronics industry.

A typical SMT assembly line is mostly automated with manual interaction limited to loading and unloading of PCBs, and setting up machines for production runs. The assembly begins with the application of solder paste using a stainless steel stencil on the regions of the board where components are to be placed. Next, a pick and place machine places components on these regions. Modern day pick and place machines are capable of placing as high as 30,000 parts per hour. The boards then pass through a reflow oven, which melts the solder paste and fuses the components to the PCB. The opposite side is populated with parts using a similar procedure.

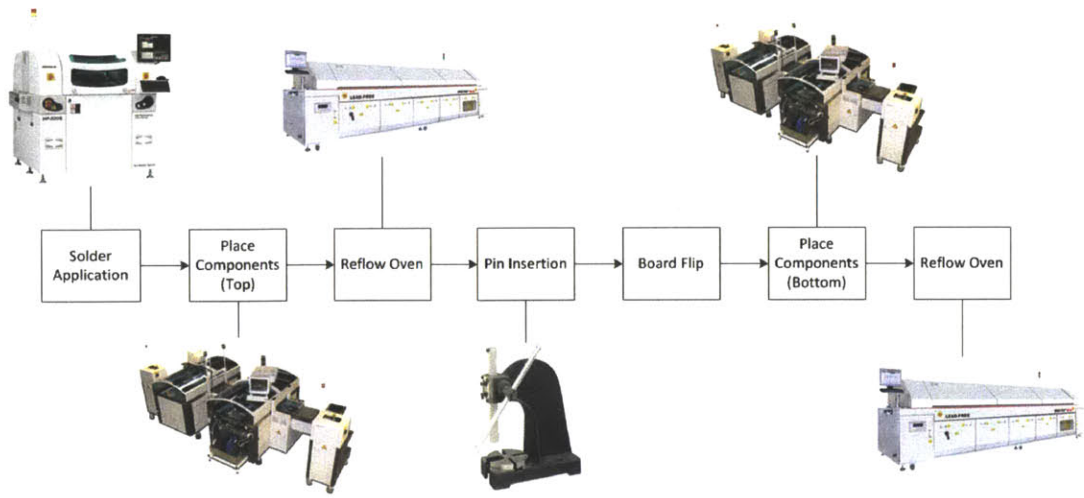


Figure 1-1: SMT Line Schematic

Current enters and leaves the circuit through conductive input output (I/O) pins (see Figure 1) that are pressed into holes in the PCB. The pin insertion process takes place between the top and bottom side SMT assembly lines. These pins come in various lengths and diameters and can be inserted into the PCBs either manually or using an automated pinning machine.


Figure 1-2: CAD rendering of pin

1.1 Motivation

The advantages of an automated pin insertion machine are higher throughput, decreased labor requirements and higher parts traceability. Although there are numerous automated pinning machines available in the market, customizing it to a companys requirements can prove to be a hard task. Machines designed for pinning may not meet the reliability and throughput requirements that the company must meet. Some of the common problems faced are reliably sorting pins from their loose state, jamming of pins, incorrect pin type being passed to the insertion head and right pin types being rejected by the system.

This thesis describes efforts in re-engineering and re-building the existing pinning machine at SynQor Inc., a designer and manufacturer of power supplies, located in Boxborough, MA.

1.2 Objectives

The project proposed to re-engineer a pre-existing pinning system into a production-ready system that is robust, cost effective, and flexible for unknown future pin types. The key objectives were as follows:

1. Develop a system which reliably sorts, orients, and inserts pins from a loose bulk state into the PCBs;
2. Achieve the desired pinning rate of inserting 8 pins in 10 seconds;
3. Produce a system that is robust while remaining easy to repair and maintain;
4. Design flexibility into the machine for use with future product lines; and
5. Integrate the machine with the companys centralized tracking system to enable parts traceability.

1.3 Scope

In this work, the project scope was narrowed to building an automated pinning machine that could efficiently insert pins of one of most widely used pin types at the company. The focus was to design a working prototype of the pinning machine, so that the company could later convert it into a production-ready machine using the same principles and mechanisms present in the prototype. The parts were designed to enable efficient interchanging of parts for various present and future pin types and sizes, while maintaining the same control system that integrated the entire system.

1.4 Work Distribution

Early in the design process, the conceptualized pinning system lent itself to three main sub-processes:

1. Sorting the pins from a loose bulk state to an oriented state;
2. Inserting the oriented pin into the PCB; and
3. Developing the vision and control systems necessary for the two previous tasks.

The initial development of each task was done as a group, but further work was split among the group members. Michelle Chang worked on the sorting of the pins from bulk to oriented state [2]. The pin insertion system was developed by Daniel Cook [3]. The author of this thesis worked on developing the vision and control system deployed in the project.

Chapter 2

System Overview

2.1 Pins

The main focus of this project is a specialized pin which is inserted into printed circuit boards (PCB). At its most basic, a pin is a cylindrical metal part with a collar. Figure 2 illustrates the maximum dimensions and features of a pin typical to the application. In total, there are 24 different pin types of varying diameters and lengths. The three diameters of pins used are 0.080, 0.062 and, the most commonly used, 0.040. Each of the three diameters has a selection of 8 different pin lengths depending on the application.

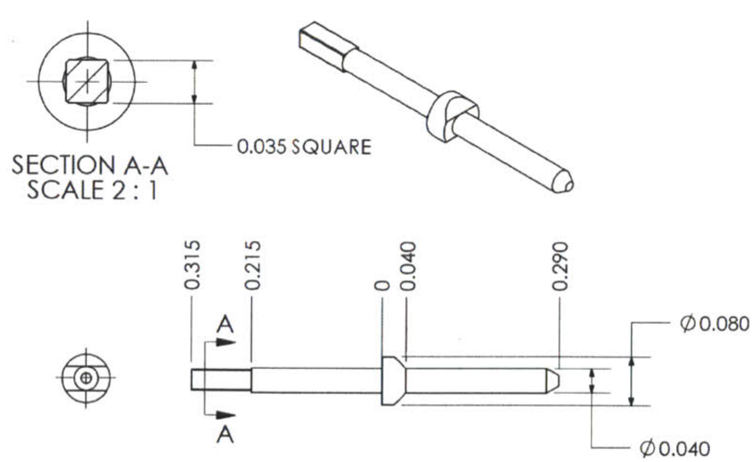


Figure 2-1: Typical maximum 0.040 pin dimensions (inches)

2.1.1 Functionality

Pins are terminal components that are used to interface between the PCB and another product. They are attached to the boards with through-hole technology, that is, the pins are inserted into holes in the board and soldered in place. By connecting via a through-hole rather than a surface-mount pad, the pins can transfer an electronic signal through the thickness of the circuit board, useful for making interconnects on a multilayer board. [4]

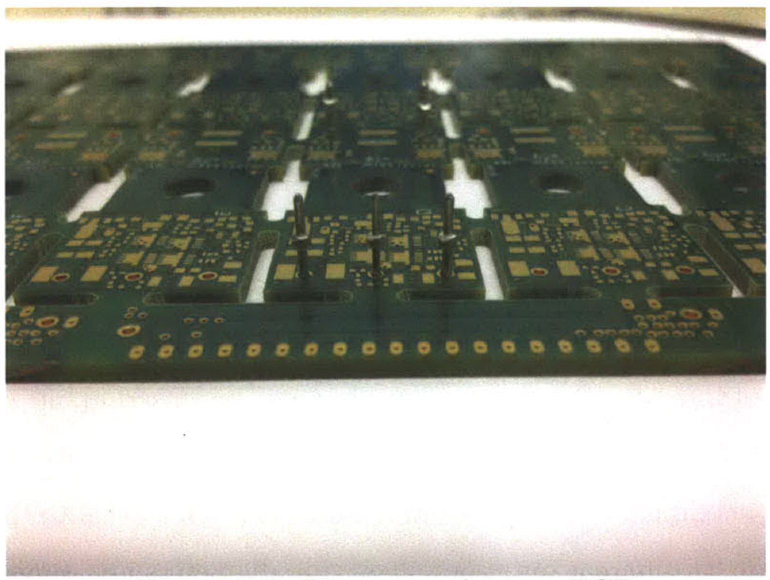


Figure 2-2: Pins pressed into a PCB

These pins are used as interconnects between PCBs and other electronics external to the board they are mounted on. While one end of the pin is attached to the PCB, the other end may interface directly with the through holes of another circuit board or with receptacle terminals on another PCB or more flexible leads. [2]

2.1.2 Project Pin Specifications

The pins involved in this project are two-sided, cylindrical rods with a collar around the center. The insertion end of the pin is characterized by a square or hexagonal insertion head (see Figure 2). The interface end interfaces with the end users terminal connections. The length of the pin on either side of the collar is variable, and the total length of these pins ranges from about 0.3 inches to 0.5 inches.

SynQor uses three diameters of pins. This project focused on the most commonly used pin diameter 0.040. On 0.040 pins, the insertion head is square. The collar on these pins is 0.080 in diameter and 0.040 long with the exception of one pin with a 0.060 long collar, intended to offset the symmetry of the insertion end and interface end lengths.

The pin is attached to the board in a two-step process. First, the pin is inserted into a PCB with an interference fit from the square or hexagonal insertion head. Second, the pin is soldered to the board. This project focused on the first part of pin attachment: the pin to board insertion process. In addition to the features noted, the pins also have two chamfers on the pin collars, which prevent solder cavities from forming during the soldering process. The pins are lead free and plated with tin. They are manufactured on screw machines and delivered in bulk in a loose state.

Figure 2-3: Pins are delivered to SynQor in a loose state in boxes from the manufacturing company

2.2 Existing Pinning Methods

There are currently three methods for pinning a PCB at SynQor. One of the methods, manual pinning, relies on an operator to manipulate the pin and insert it into the board. The other two methods are two different approaches to automating the pinning process. The three processes and the inefficiencies inherent to them are detailed in this section.

2.2.1 Manual Pinning

Pinning a board manually utilizes an arbor press with a special collet with negative pressure to retain the pin. To set up the process, the operator adjusts the depth stop on the arbor press by test inserting pins until the correct depth is achieved. Once this height is achieved and confirmed by measuring the depth, the operator locks the depth stop in place. At this point, the set up for the manual pinning process is complete.

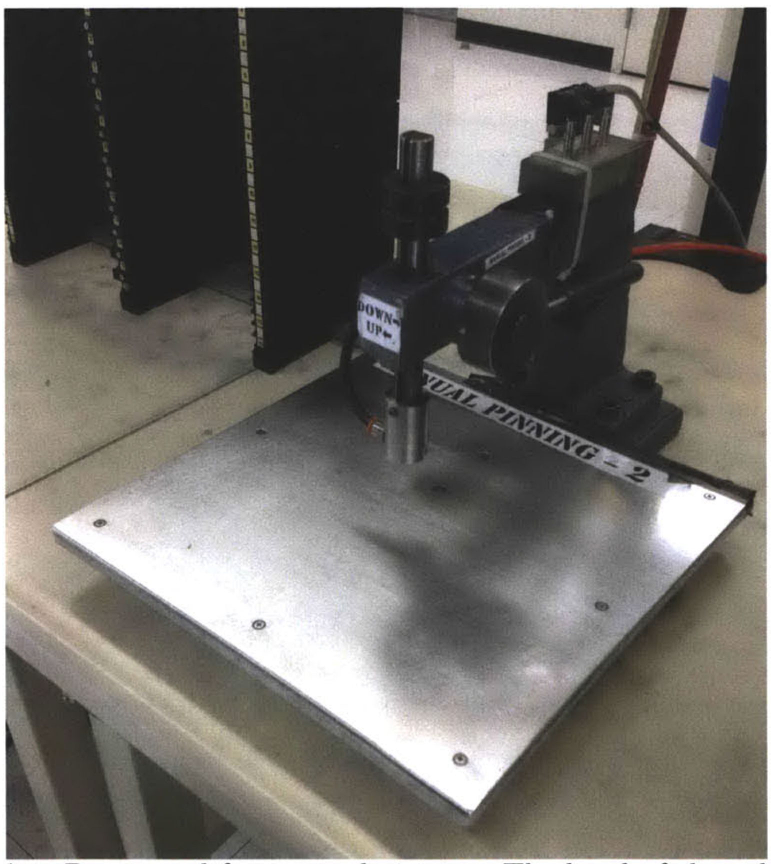


Figure 2-4: Arbor Press used for manual pinning. The head of the arbor press has a collet on it to hold the pin that is attached to vacuum pressure. The vacuum pressure holds the pin in the collet and prevents it from falling out.

The operator takes a pin from the box of pins, inserts the head of the pin into the collet, and then locates the circuit board under the press according to a drawing the details where each pin, and what type of pin, should be located. The board is populated with pins, and moved into a queue for the next process.

The operators scan each board into the SynQor production tracking system as they are pinning it, as well as the box that they are pulling pins from. Tracking pins in this manner provides some level of part traceability, but is prone to errors since often times there are multiple boxes of pins available for the operators to pick from.

Currently, the manual pinning process is run with two to three full time operators, for two shifts per day, depending on the workload. Manual pinning is labor intensive and costly. The goal is to reduce labor requirements with the process developed herein.

2.2.2 Automated Pinning-Flexible Automation

SynQor developed a pinning machine, working in conjunction with an outside company in the early 2000s. The idea was to develop a process that allowed an operator to load up to 8 different pin types in vibratory bowls and have the machine feed pins, orient them, and then send them to an insertion machine to be inserted into the board without operator intervention.

The system works by feeding the pins by means of a vibratory bowl feeder to a conveyor. The conveyor transports the pins past a line-scan camera where an image is developed from the slices that the camera takes. From the image that the system builds, it analyzes the pin and determines if it is the correct pin, and if it is in the correct orientation. Downstream from the camera, an arm picks up the pin and reorients it (if necessary), then sends it through a tube by means of compressed air to the insertion robot. The robot picks up the pin and positions it at the correct point over the PCB and presses the pin to the correct depth.


Figure 2-5: Dual-gantry pinning system

This machine was used in production briefly when they first purchased it, but it was prone to failures. The machine struggled to deliver pins reliably to the insertion robot. There were issues with pins jamming at certain points in the system - frequently in the tube that delivered pins from the sorting mechanism to the insertion robot. The sorting mechanism was often not able to identify and re-orient pins fast enough to keep up with the pace set by the insertion robot. This problem often led to the insertion robot sitting idle while it waited for a pin.

The positioning system (a dual-gantry Cartesian robot see section 3.3) from this machine, as well as the production system interface (barcode scanning, board programming) will be re-used in the present project in its pre-existing form, with little modification.

2.2.3 Automated Pinning-Specialized Automation

Another pinning process was developed by SynQor with a different outside company. This system, decidedly less flexible in terms of the variety of pins it can handle, as well as how it handles faults, employs vibratory bowl feeders to feed and orient the pins. The bowl feeders are customized to accept and sort different pin types. The pins are sorted mechanically by taking advantage of the non-symmetric design of the pins which allows the bowl feeders to reject pins that are not in the desired orientation.

Once the pins go through the sorting and orientation process, they line up in a queue upstream from an escapement. The escapement picks off one pin from the queue of pins and drops it down a tube to send it to the insertion head. The board is positioned under the insertion head and a pin is driven to the desired depth.

Figure 2-6: The vibratory bowls of this pinning system can be seen atop the machine enclosure. These bowl feeders send pins to the insertion head inside of the machine.

This system suffers from frequent jamming in the bowl feeding/escapement area of the process. Since the bowl feeder is vibrating, some pins can ride up on each other and cause the queue to jam which requires an operators attention to clear the jam. The positioning system in this machine has very little in terms of feedback to know if it has pressed a pin correctly.

2.3 Developed Solution

The team has developed a pinning process that accepts pins in bulk (loose) then sorts and transports them to an insertion machine that inserts them into the PCB. The processes of sorting and insertion have been decoupled by means of a pin magazine that stores pins between the sorting and insertion process. A systems level overview of the process is given in this section.

2.3.1 Overall Pinning Process/Final Design

The pinning process consists of two major sub-processes: sorting and insertion. The two processes were run in series in past attempts to automate pinning, which resulted in the sorting process holding up the insertion process quite often due to jams or other faults. The decision was made to decouple these two processes, in order to be able to run the processes in parallel without running into any issues where one processes causes the other to slow or stop.

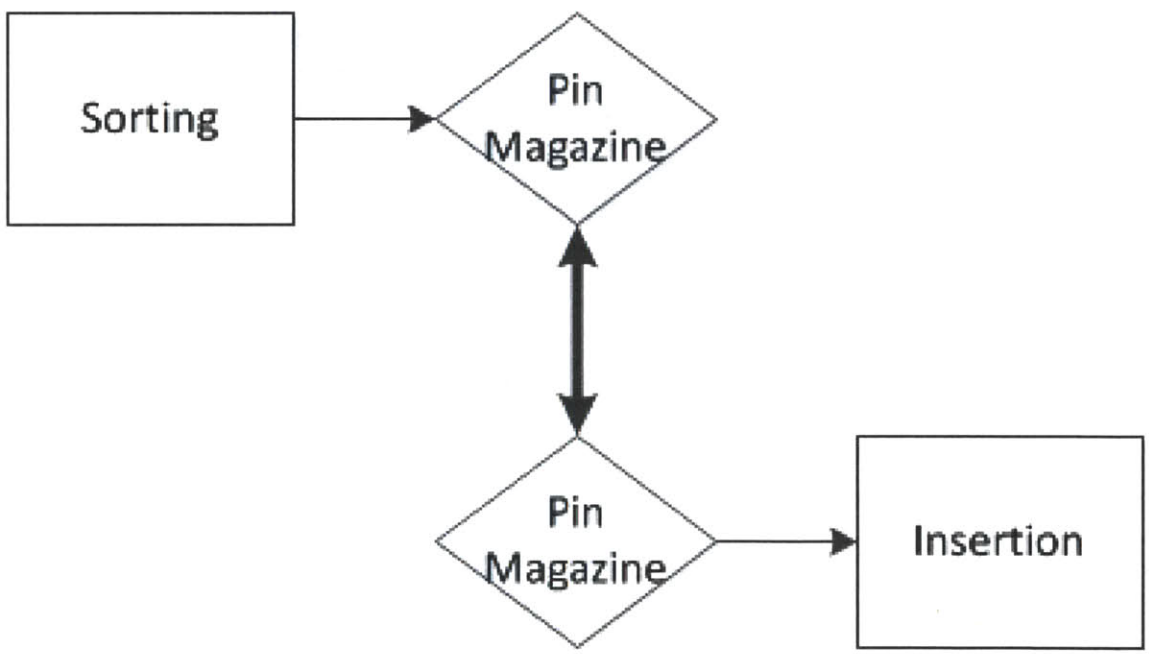


Figure 2-7: Pinning Process Diagram

The system was decoupled in between the sorting and insertion sub-processes by designing a magazine to hold a determined quantity of pins that would act as the interface between the sorting process and the insertion process.

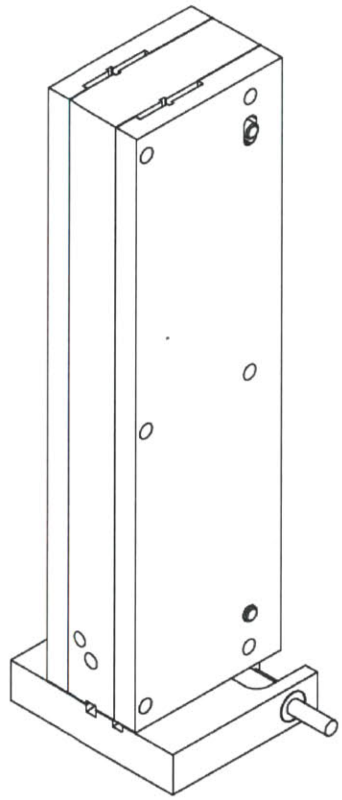


Figure 2-8: Magazine used to interface between sorting and insertion process

Sorting

The process of sorting pins brings the pins from the loose state in which they are delivered to SynQor and aligns them in the pin magazine. The sorting process utilizes vibratory bowl feeders to singulate the pins, and then transports them to a rotating wheel that grips the pins and brings them in front of a camera. The camera and the accompanying vision system analyze the pin and determine if it is in the correct orientation and if it is the correct pin. After the camera stage, the pin either is sent directly to the magazine if it is in the correct orientation, or it gets sent to a reorientation stage before being sent to the magazine.

The sorting process is something that will be done away from of the production floor, likely in the stockroom. When pins arrive at SynQor, operators will run them through the sorting machine to populate the magazine so the magazines are ready for the production floor.

Insertion

Once the pins are sorted into a magazine, the insertion process can begin. The insertion machine consists of two gantry-style Cartesian (see section 3.3) positioning robots. Attached to each carriage on the robots are two insertion mechanisms. In all, one gantry has an insertion mechanism for 0.040 diameter pins and 0.062 diameter pins, and the other has a mechanism for 0.080 diameter pins and an additional mechanism for 0.040 diameter pins. The 0.040 pins are the highest volume pins run at SynQor, so there are two insertion heads (one on each gantry) to handle them so the workload can be balanced between the two gantries.

The insertion mechanism utilizes the feed drum integrated into the magazine to pull pins off of the bottom of the stacks and rotate them around to the bottom of the magazine. Once a pin has been rotated around to the bottom of the magazine, it falls to an insertion tube that rotates to orient the pin vertically. From here, the positioning gantry locates the pin over the correct hole on the board and proceeds to drive the pin down to the correct insertion depth.

The process repeats until a magazine is depleted, or a new pin type is required for the board. In either case, the positioning robot can automatically unload an empty or un-needed magazine, and load a new one from a magazine rack located within the positioning robots work envelope.

2.3.2 System Components

There are a number of features already implemented in the positioning system that have been developed prior to the start of this project at SynQor. We have re-used a number of these features as part of the pinning process.

The positioning system has the ability to scan the barcode located on each PCB to determine the correct part program to run for that particular board. This feature allows the machine to change product lines without operator intervention since multiple pin types can be loaded into the magazine rack. A product-programing interface has also been developed to allow engineers to easily program new PCBs. This interface makes the pinning machine flexible when introducing new products to the assembly line.

Chapter 3

Automation

The transition to automated assembly processes from manual processes has been the focus of a number of companies that perform repetitive, semi-skilled assembly tasks to build a product. It is especially true in high-wage regions. The pinning system discussed in this thesis is a good example of the justification for automation, as well as the development process to design an automation process and the accompanying equipment.

As such, it is important to have an understanding of how industrial automation came to be what it is today, and where the current focus is on advancing the field. This section proposes to give the reader an overview of automation to set up the context for the process and equipment design discussed later on.

3.1 Defining Automation

At its most basic, automation can be defined as the use of machines which make a manufacturing process more efficient. The machines combine operations or have skills that are not easily acquired by a human workforce. But automation is not simply making a single process automatic; automation is the automatic handling and continuous processing of a machine, made possible with computer control. Automation processes can be considered part of the more general category of computer integrated manufacturing (CIM).[6]

It is important to differentiate automation from mechanization. Mechanization is doing work with machines. That is, operators use machinery to assist them in completing the bulk of their work. Automation reduces the human physical labor component by making much of the work automatic, controlled by computer technology. Automation operators are mainly responsible for making sure the machines are in working order, rather than actually for making the parts. [7]

Automation is characterized by the use of electromechanical devices such as motors, servos, hydraulic and pneumatic systems; an increase in the productivity of a given process; improved precision and reproducibility; and a decreased labor force in purely physical work.

3.2 Brief History

The advent of automation as we have defined it came hand in hand with the development of the more complex control systems, chiefly through advances in digital computing. The term automation itself was first used at the Ford Motor Company in 1945 to describe the combination of automatic handling and continuous processing in machines. [6].

The roots of automation can be traced to the electrification of factories. As it became possible to provide machines with electric motors, many already mechanized processes were combined in machines, and factories were able to implement continuous-flow mass production. These machines were all tooled specifically for their tasks though use of cams. The need for more flexible and sophisticated machine control became evident. Numerical control (NC) grew from this need. [8].

Numerical control is what drives much of modern precision machining. This positioning control is the technology behind the CNC (computer numerical control) machines that are viewed as a trademark of automation.

Early forms of machine control included cams and tracing machines, but these methods were not abstractly programmable. The development of the servomechanism and the subsequent selsyn (basically two servos together) meant it was possible to have highly accurate measurement information. The idea of combining this positioning system with a numerical calculator was first brought together by John T. Parsons in the 1949, with punch card readings as the calculator. [8].

The first working NC machine was developed at MIT in 1952 a complex design involving a punch tape input, relay-based hardware registers, and many encoders and moving parts. The following decade showed many improvements to CNC systems, but it was not until the proliferation of minicomputers in the 1960s that the use of CNC machines became widespread [8].

This positioning control technology has had usage beyond the field of machine tools. The precision positioning systems developed for machining have been extended to control of autonomous robots, many in the service of factory automation. The first such robot was the Unimate, used in a General Motors plant in 1961. The robot moved die castings and did welding, jobs considered extremely dangerous for human laborers. The trend in automation has continued today, with many robots doing the duties that humans cannot or would not want to perform. [8].

3.3 Dynamics/Configurations

There are a number of different configurations of industrial robots, each suited for different tasks. Each robot is a combination of different types of linear or rotational joints that can be manipulated in order to reach the desired position. Common configurations include the SCARA robot (Figure 5), typically used for simple pick-and-place type operations, Articulated robot (Figure 6), which has the dexterity and similar joint structure to a human arm, and the Cartesian coordinate robot (Figure 7), which is often seen in a gantry configuration [9]. Each robot has a characteristic work envelope which represents the volume that the robot can reach with its end effector.

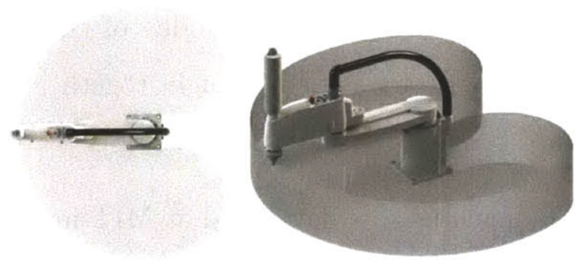


Figure 3-1: Typical SCARA robot with work envelope shaded in grey [10]

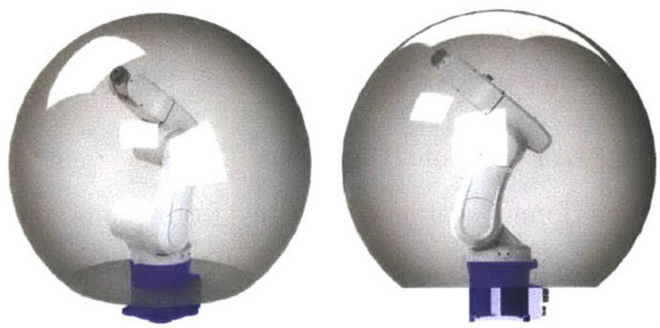


Figure 3-2: Typical articulated arm robot with work envelope shaded in grey [11]

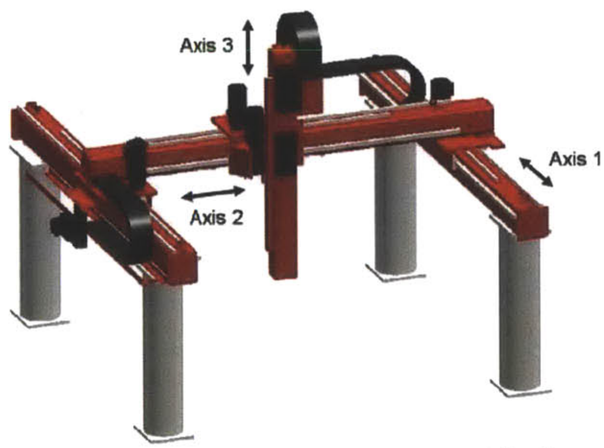


Figure 3-3: Typical gantry robot [12]

The gantry (Cartesian) robot configuration used at SynQor provides a robust structure to position objects in 3D space. Unlike the other two configurations shown (SCARA and articulated arm), the gantry configurations axes are well supported on both ends, and do not have any cantilevered joints or frame members. Well supported joints and frame members deflect less under load, which increases the positioning accuracy of the robot.

A robot has three main coordinate systems which represent its work envelope.

These coordinate systems are [13]:

1. Joint Coordinates: coordinates that store the exact position of each joint in the robot to reach the desired end effector position. These coordinates are stored as positions of each joint relative to a local reference frame.

2. World Coordinates: describe the position of the end effector relative to a fixed coordinate frame attached to the ground. In some cases, multiple joint orientations might satisfy the desired world coordinate position.

3. Tool Coordinates: a coordinate frame is fixed to the center point of the tool on the robot. Using the tool coordinates, the robot can be programmed incrementally, without dealing with the kinematics of the robot itself since all motions are relative to the tool.

Robots can be programmed in a variety of manners. On-line programming involves programming the robot directly, which often requires taking the robot out of the production process that it is currently being used in. Off-line programming, however, utilizes computer simulation or a physical model of the robot to program the desired motions. Once the program has been generated off-line, it can be uploaded to the robot on the production line, which minimizes downtime compared to on-line methods.

Programming the motion of the robot can be accomplished in a number of ways. Text based programming methods with proprietary languages such as AIM, or V+, as well as general motion control languages that are based on Visual Basic, or C can program precise motions of the robot, as well as take advantage of conditionals and loops within the program. Physical programming methods include teaching the robot points by physically moving the end effector to the desired position, then recording the sequence of points; as well as playback programming which involves teaching the robot the path it should follow between points to have more control than point to point motions.

The tool on a robot is often used to hold a part, or to hold a tool being used in a production process. Robots that hold a part often have some type of gripping mechanism as an end effector. The gripping mechanism can physically grip the part with pneumatic or electric actuation, or it can hold the part via vacuum, or magnetics. Robots that hold a tool used in a production process will often have specialized end effectors to accommodate that tool and the accessories that go along with it. [13, 9].

3.4 Economics of Automation

With the increasing cost of labor in developed countries, automation has gotten a lot more attention from manufacturing companies that wish to continue manufacturing in high-wage environments. Additionally, with the increasing cost of labor, the price of industrial automation (i.e. robotics) has been decreasing steadily.

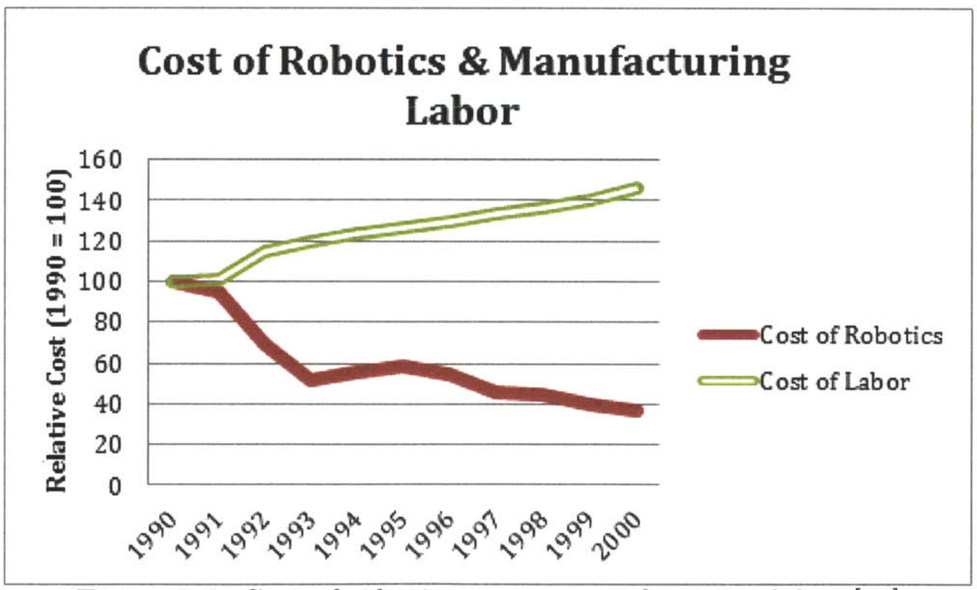


Figure 3-4: Cost of robotics versus manufacturing labor [14]

In addition to the financial reasons to use automation, automation can also relieve humans from performing dangerous, hazardous, or menial tasks that are not well suited for humans to perform. Tasks that involve hazardous chemicals or materials, are performed in clean-room environments, or operate in hard-to-reach places are particularly well suited for robotics.

3.5 State of the Art

Current automation research focuses on two main areas:

1. Increasing the intelligence of robots through machine learning and vision systems, and

2. Increasing the speed and accuracy of existing robotic systems.

3.5.1 Machine Vision

Machine vision has revolutionized the field of manufacturing automation by decreasing the time required for processes like inspection, counting, gauging, defect detection, thereby reducing labor requirements significantly. The advantages lie in the fact that these processes are carried out with more precision, have become faster and more reliable. Industrial machine vision systems are deployed in almost all industries like semiconductors, electronics, automotive, pharmaceutical and food packaging.

Cameras used in present day vision systems are based on Gigabit Ethernet (GigE) vision interface standard that allows data transfer rates up to 1000 Mbit/s [15].Acquisition speed is an important parameter that defines how fast the system can capture and process images. Today, the fastest systems in the world can process up to 500 frames per second [16]. On the other hand, the size of the camera and the on board processor has decreased. The smallest camera available in the market is 30mm X 30mm X 60mm [17]. It must be noted that the processor is also embedded inside this tiny camera, making it an efficient inspection system where space is a constraint.

Along with the hardware, a lot of development has taken place in vision software to enhance image-processing capabilities, capture more intricate details of the image and provide better results. Multi-core processors significantly reduce the processing speed and also enable controlling of up to 8 cameras simultaneously [18]. Some of these processors have additional features that can handle I/O from various systems, thereby eliminating the need for a separate PLC [19].

Features like pattern matching and edge detection have been the most commonly used features in machine vision systems. But in recent years, developments in computer algorithms and processing speeds have facilitated the introduction of newer features for image editing and processing.

Present day vision systems are not just cameras connected to a powerful processor, but also possess various sensors needed in manufacturing automation. One of the most commonly used sensors in industrial automation is the photoelectric sensor. All-in-one industrial inspection systems with embedded photoelectric sensors, camera, lighting and optics capable of inspecting up to 6,000 parts per minute are revolutionizing the world of manufacturing [20].These low form factor inspection systems eliminate the need for expensive fixturing and simplify the overall system design. Most vision systems have a fan less design making them conducive to be used in clean room environments [18].

Systems with network protocols like RS-232, RS-485, Ethernet built on them enable multiple systems to be controlled all at once via a LAN or VPN connection. Additionally, some software also provide web based monitoring of the production process, thereby reducing manual interference to the bare minimum [21]. These features make the remote management of systems and generation of production reports very easy to achieve.

Machine vision is being integrated with robots to help them make judgments on the basis of what they see. Machine vision based robots are being used in solar cell manufacturing to enhance the throughput and quality [22]. Most components used in solar cells are delicate and small, and require complex assembly. Physical tracking through conveyor encoders require additional tooling and fixtures, which can be eliminated by vision based inspection, thereby bringing considerable savings.

The industry is slowly moving towards 3D machine vision. 3D vision helps in capturing details about the depth of the object [23]. This is especially used in semiconductor and food industries, where thickness of the object plays an important role and also in inspection of molded parts to look for defects.

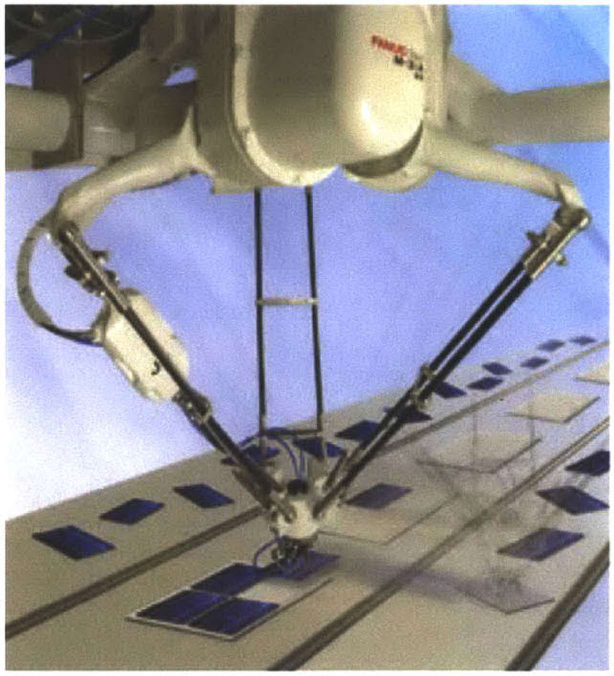


Figure 3-5: 6 axes robot integrated with machine vision used in solar cell manufacturing [22]

In this age of economic sluggishness, as manufacturers try to keep manufacturing competitive despite increasing labor prices and competition from cheaper markets, machine vision based manufacturing automation helps bring in cost effectiveness by reducing both labor and footprint.

3.5.2 Robotic Improvements

The speed and accuracy of a robot is a factor of the structural design of the links between the different joints, the power that the joint actuators can provide, and the resolution to which the joints can be controlled.

Currently, the fastest robot on the market is the Adept Quattro robot, which has a parallel configuration of four arms (see Figure 10 - Adept Quattro parallel configuration robotFigure 10). The Quattro has a payload capacity of 6kg, a maximum speed of 10m/s, and a repeatability of +/- 0.1mm.

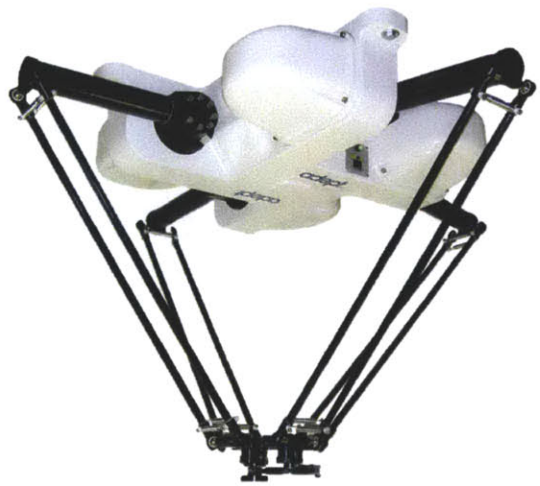


Figure 3-6: Adept Quattro parallel configuration robot

Chapter 4

Machine Vision Systems: A Background

In the pin insertion machine, a machine vision system is used to identify the right pins and their orientation. Building a complete machine vision system requires a good understanding of the hardware components, image processing software and other accessories. This chapter proposes to give a detailed description of the hardware and software tools used. The background algorithm of some of the image processing tools, essential qualities of a camera and accessories is presented, so that the machine vision application development presented in Chapter 6 is easy to understand.

4.1 Overview

Machine vision systems are being increasingly deployed in numerous industries to increase accuracy and decrease production time and labor requirements. Some of these industries are electronics component manufacturing, quality textile production, metal product finishing, glass manufacturing, machine parts, printing products and granite quality inspection, integrated circuits (IC) manufacturing and many others [24].

A machine vision system typically comprises a camera, a processing unit with I/O channels and a lighting system. In an automated inspection system (AVI), the vision system is usually triggered from an external source like a PC or a Programmable Logic Controller (PLC). A light source illuminates the object in such a manner that all the features to be captured are conspicuous. A camera then captures an image and digitizes it. Next, the captured image is processed to modify the pixels to extract required information from it. Segmentation is the process by which an image is partitioned to identify certain key features present in it. Some of the commonly used features have been discussed Section 4.2. Based on the features, the system can be programmed to do few basic tasks like presence/absence of a part, calculating critical dimensions and alignments [25].

The results of these tasks can be used for the following [24]:

1. Control an assembly process (guide a robot to pick and place different components based on the result)
2. Transfer the data to another device through a network to store information
3. Identify faults and defects and corrective actions like replacing the part or rejecting the product.

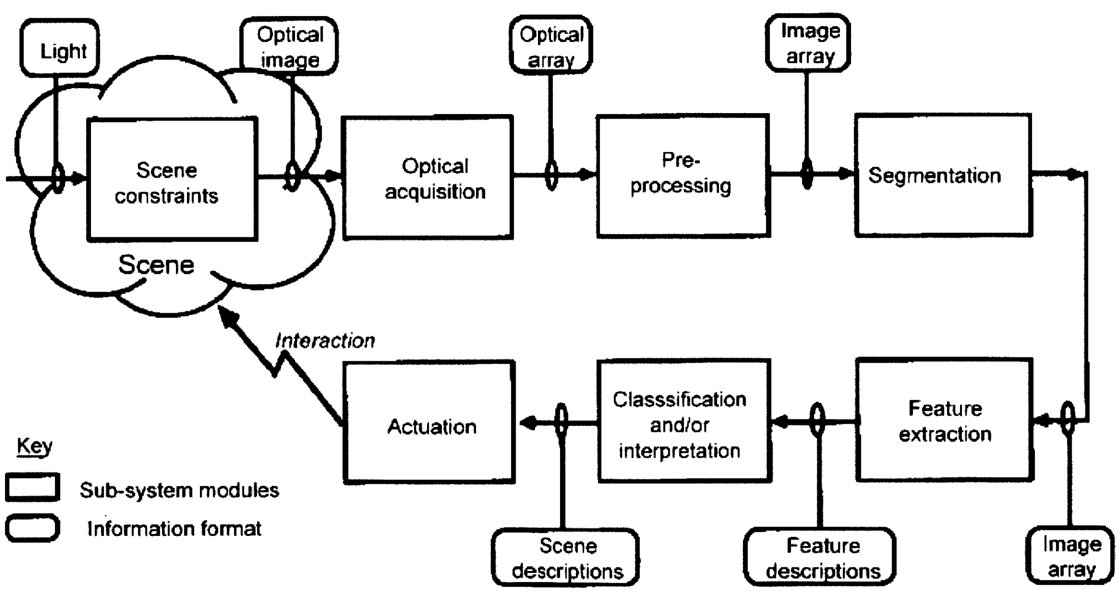


Figure 4-1: A simple block diagram for a typical vision system operation [26]

The following sections deal with each of the components of a machine vision system.

4.2 Commonly Used Tools

A lot of tools are used in machine vision systems to detect certain features in an image. The application developed for this project used (a) pattern recognition and (b) edge detection. These are the 2 most commonly used tools in the industry.

4.2.1 Pattern Recognition

In simple terms, pattern recognition is defined as classification of input data via extraction of important data from a lot of noisy data [27]. In other words, a vision system looks for certain features that it has been taught to look for in captured image.

In the pinning machine project, pattern recognition is used to identify the orientation of the pin. An image of the top half of the pin is used as the reference. Using this reference, the system detects whether the captured image falls under one of the 2 classes, right or wrong orientation.

Pattern recognition strategies are broadly categorized into 2 [28]:

Structural Method

Structural Methods rely on primitives like horizontal lines and curves to make a decision. The system forms a relationship between the primitives and looks for the same relationship in the captured image [28].

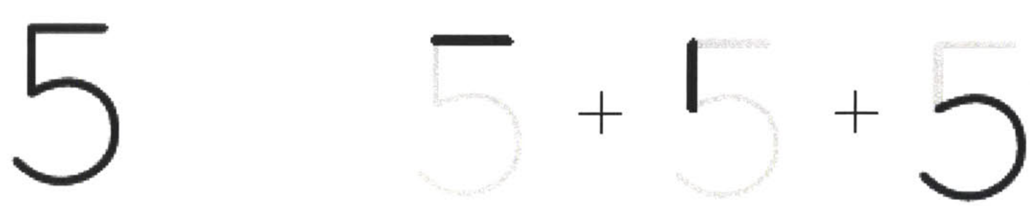


Figure 4-2: Structural features for the number 5, a horizontal and vertical line, and a curve [28]

4.2.2 Statistical Method

Statistical pattern recognition is based on Bayesian decision theory. The features of the image are stored in a vector x and in simple cases, there are two classes (ω_1,ω_2)in which it can fall. For a given x, if

$$P(\omega_1) > P(\omega_2)$$

the vector x falls into $_1$ category and vice-versa. If $P(\omega_1)=P(\omega_2)$, it could be part of both classes [28].

4.2.3 Edge Detection

Successfully rejecting wrong pin types from the system is one of the most important tasks of the vision system. The vision system accomplishes this by calculating key dimensions that can uniquely identify a pin. Dimensions are calculated by detecting edges and subtracting the distance between them.

A vision system defines an edge as a significant local change in the image intensity. There are mainly 2 kinds of edges [26]:

- Step Discontinuity: The image intensity abruptly changes from one value to the other.
- Line discontinuity: The image intensity abruptly changed value, but returns to the original value within a short distance.

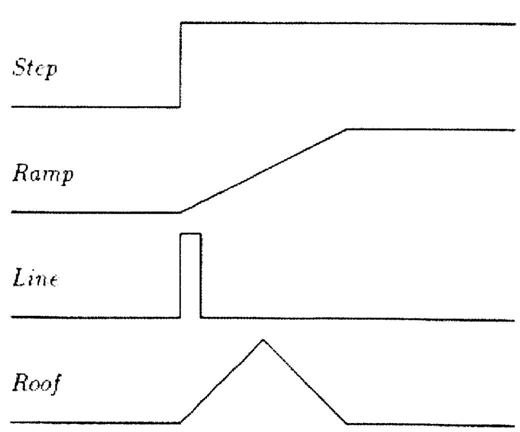


Figure 4-3: One dimensional edge profiles [26]

Other discontinuities like ramp and roof are functions of step and line discontinuities.

4.3 Illumination

Illuminating the object plays an important role in the quality of the image obtained. A well lit object will make the desirable edges and patterns more conspicuous, while eliminating noise and other external factors.

In the early days of machine vision, readily available sources of light was used to illuminate the object, which led to disastrous circumstances [25]. This led to a lot of development in lighting and illumination techniques.

4.3.1 Desirable Properties of an Illumination System

Some of the important properties that are required of an illumination unit are [25]:

- Ability to control lamp brightness
- 3D radiation pattern
- Electrical noise generated
- Shape
- Long term degradation of emitted power
- Driver (Closed loop, AC/DC, frequency)

A poor illumination system can produce glares and shadows, thereby affecting the final results adversely.

4.3.2 Effect of Ambient Light

Ambient light was an important factor while designing the vision system for the pin sorting mechanism. It was found that shutting out ambient light made the image sharper and led to better results. In other words, ambient light acts as 'noise' while capturing images of the pins. The mechanism used to shut out ambient light has been discussed in the Chapter 6.

The presence of ambient light input can have a tremendous impact on the quality and consistency of inspections, particularly when using a multi-spectral source, such as white light. The most common ambient contributors are overhead factory lights and sunlight. There are 3 active methods for dealing with ambient light high power strobing with short duration pulses, physical enclosures, and pass filters. High-power strobing simply overwhelms and washes out the ambient contribution, but has disadvantages in ergonomics, cost, implementation effort, and not all sources can be strobed, e.g. - fluorescent. If strobing cannot be employed, and if the application calls for using a color camera, multi-spectral white light is necessary for accurate color reproduction and balance. [27]

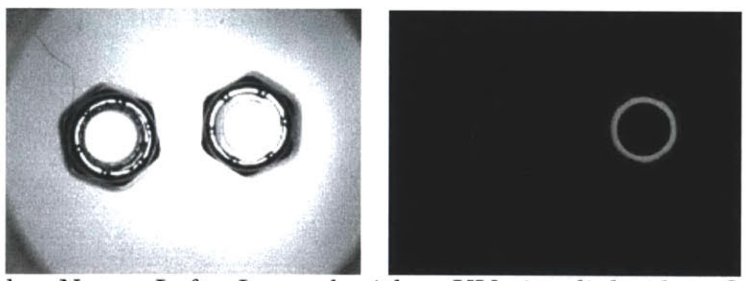


Figure 4-4: Nyloc Nuts. Left: Imaged with a UV ring light, but flooded with red 660 nm ambient light. The goal is to determine nylon presence / absence. Given the large ambient contribution, it is difficult to get sufficient contrast from the relatively low-yield blue fluoresced light from the sample. Right: Same lighting, except a 510 nm short pass filter was installed on the camera lens, effectively blocking the red ambient light and allowing the blue 450 nm light to pass. [27]

4.3.3 Types of Lights Available

Some of the commonly used light sources are [25] : Incandescent filament lamps Fluorescent lamps Discharge lamps Light emitting diodes (LED) LEDs have become the common source of lighting for machine vision applications. Other sources have various disadvantages like uneven lighting, short life and high electrical noise.

4.3.4 Light Emitting Diodes

A ring shaped front lighting unit was used to illuminate the pins in the present project. It is one of the most commonly used lighting units and was found to be sufficient for obtaining good images.

LEDs provide and ideal light source for many vision applications. Owing to their tiny size they can be arranged in various shapes and spectral characteristics to deliver the required intensity of light that suits the application. They consume low energy and are electrically safe as they operate under low voltages. Most LEDs typically have a life of 50,000 hours [25].

LED lighting units for vision system applications come in various shapes and sizes. They can be a linear array, dome shaped, ring shaped among others.

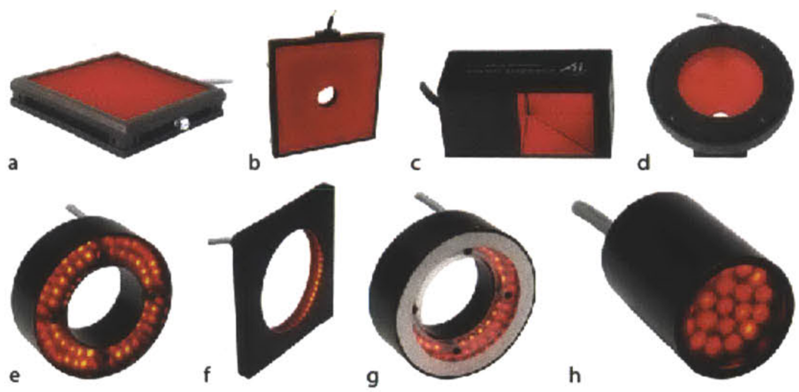


Figure 4-5: (a) Backlight (b) Diffuse Illuminator with central viewing (c) Coaxial illumination (d) Omni direction light source (e) Ring light (projects forwards) (f) Ring light (projects inwards) (g) Ring light (projects both inwards and outwards) (h) Spot light [25]

4.3.5 Illumination Techniques

The following illumination techniques can be used independently or as a combination to capture required features of an image [27]:

- Back lighting
- Diffuse lighting
- Bright field

- Dark field

The front light unit used in the vision system is of on-axis diffuse lighting type.

Back Lighting

Back lighting is used to create a dark silhouette of an object against a bright background. It can be used to detect presence/absence, edges of objects, detection of holes/gaps.

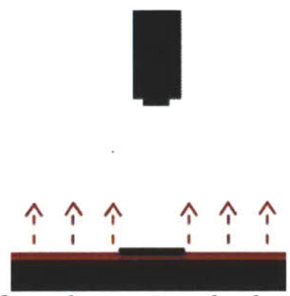


Figure 4-6: One dimensional edge profiles [26]

Diffuse Lighting

Diffuse lighting can be of 2 types: dome and on-axis. Dome axis lighting is used to illuminate curved surfaces effectively, while on-axis is used for linear surfaces. They are usually placed very close to the sample.

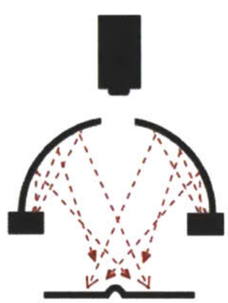


Figure 4-7: Dome shaped front lighting

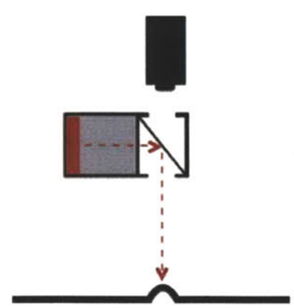


Figure 4-8: On-axis lighting

Partial Bright Field

It is the most common type of light we use in our daily lives, including sunlight. As opposed to full bright lighting, it is directional and usually from a point source. Due to these qualities, it is effective in enhancing topographic details.

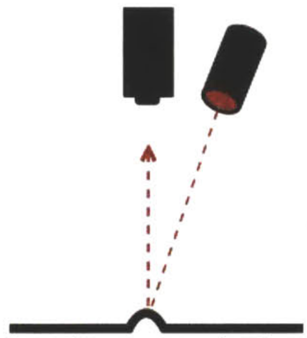


Figure 4-9: One dimensional edge profiles [26]

Dark Field

The characteristics of dark field lighting are low angle of incidence requiring close proximity to the object.

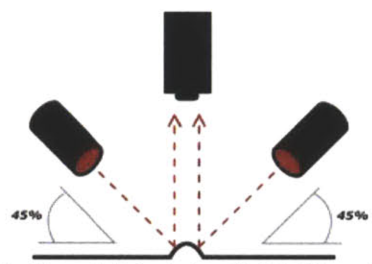


Figure 4-10: Partial bright field illumination [27]

Chapter 6 has a detailed discussion as to how the required hardware and software tools were selected from the ones available to build the machine vision application.

Chapter 5

Control System Design

5.1 Overview

The two main functions of the pin insertion machine are to sort and align pins, and to insert these sorted pins into the PCBs. Each of these 2 processes involves multiple mechanical movements that need to be co-ordinated and timed so that the machine functions smoothly. Some of these include reorienting pins, loading pins into the magazine, transferring pins from the magazine to the insertion arm, swinging the insertion arm, among others. These mechanical motions are controlled using programs that 'tell' the hardware components when to do a particular task. The control system design integrates all components involved in the sorting and insertion process.

A Programmable Logic Controller (PLC) is used to co-ordinate the various sequential steps involved in both pin sorting and insertion. The program is written on a computer and then downloaded onto the PLC, which then controls the system based on the program. As the sorting and insertion processes are decoupled and hence independent of each other, separate PLCs are used to control the 2 processes.

This chapter describes the hardware components used in the designing the control system, wiring the components to the PLC and the software design for the control system.

5.2 Components

Some of the important components that were used to build the automated pin insertion machine are:

5.2.1 Pneumatic Valves

Pneumatic valves were used both to blow compressed air and to create vacuum. The pin insertion part of the machine has vacuum generators to suck pins from the magazine to the insertion head. Positive pressure valves were used for 'pin blast', or to blow the pins from the magazine to the insertion tube. These valves have solenoids in them, which can be energized by supplying a 24V DC signal. Figure 5-1 shows the Festo MYH-5/2-2.3-L-LED Directional Control Valves used in the insertion machine.

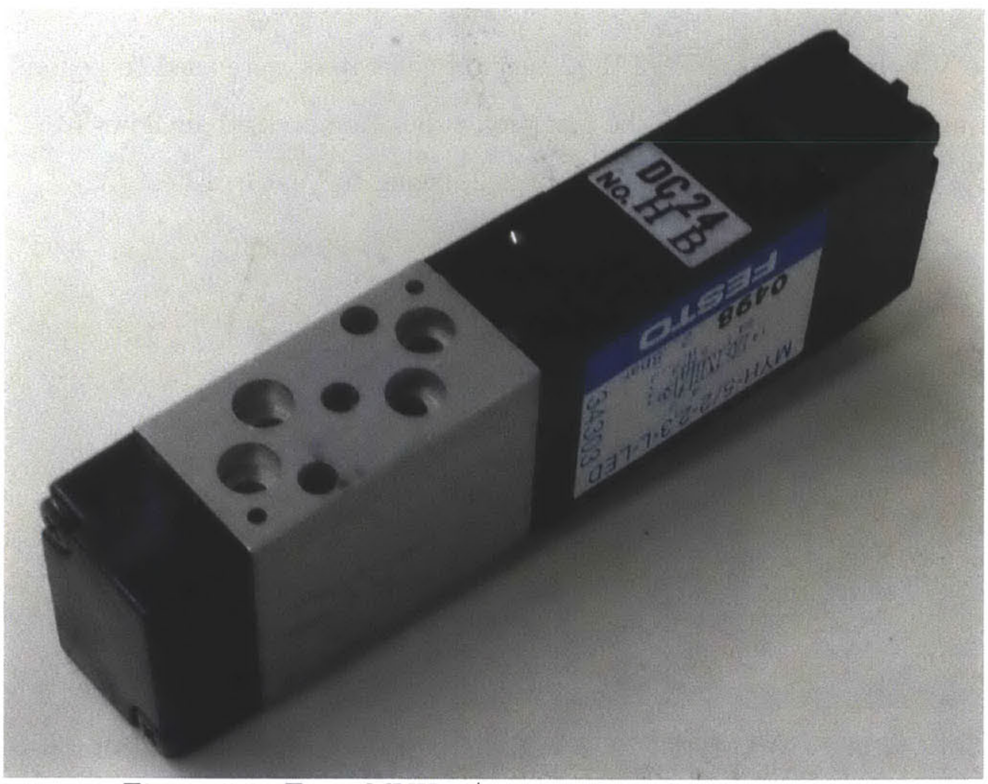


Figure 5-1: Festo MYH-5/2-2.3-L-LED Solenoid Valve

Figure 5-2 shows the schematic of a 5/2 DCV with spring loaded manual override. 14 and 12 are the solenoid and the manual over-ride buttons respectively. 4 and 2 represent the actuator ports, while 5 and 3 represent the exhaust ports. The pressure port is represented as 1. The schematic describes the un-actuated position, or the state in which the solenoid 14 is de-energized. When 14 is energized using a 24V DC signal, compressed air flows from pressure port to actuator port 4, while air leaves from 2 through exhaust port 3.

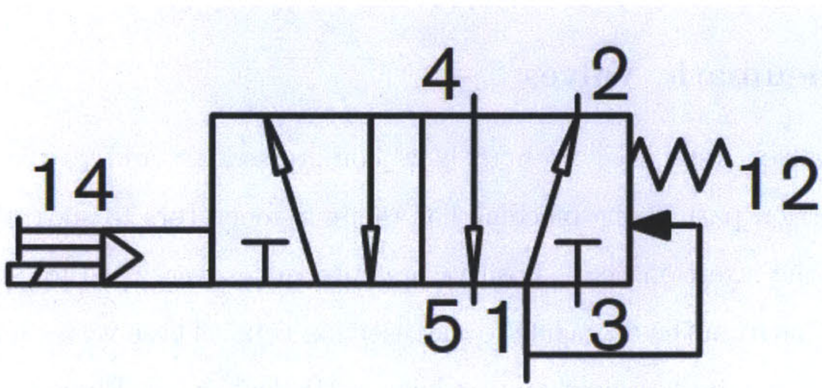


Figure 5-2: Symbol of a solenoid actuated 5/2 DCV with manual over-ride. On energizing the solenoid, compressed air flows from port 1 to port 4 [31]

Festo VN-05-H-T3-PQ2-VQ2-RQ2 vaccum generators were used to generate vacuum required to suck pins into the insertion tube. Compressed air flows from port 1 to port 3, while creating a vacuum at port 2, owing to Venturi Effect [32]

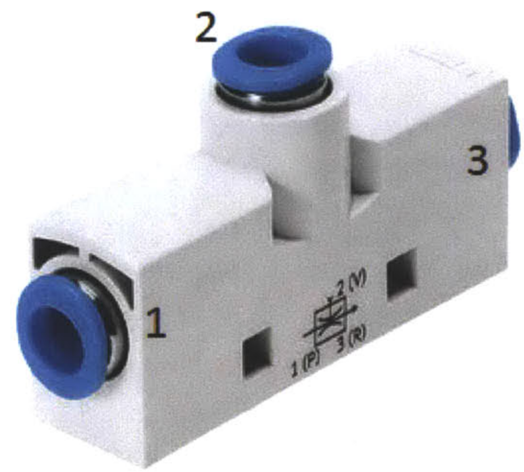


Figure 5-3: Festo VN-05-H-T3-PQ2-VQ2-RQ2 vacuum generator. Compressed air flows in-line from port 1 to port 3, creating vacuum at port 2 [34]

The vacuum generators used in the pin sorting machine are ones that can generate vacuum as well as blow compressed air through the same port. Figure 5-4 shows the VAD-M-I vacuum generators from Festo. These consist of 2 control valves that are controlled by separate solenoids that must be energized and de-energized independently.

Figure 5-4: Festo VAD-M-I vacuum generator. It has 2 solenoids, one for compressed air and the other for vacuum [33]

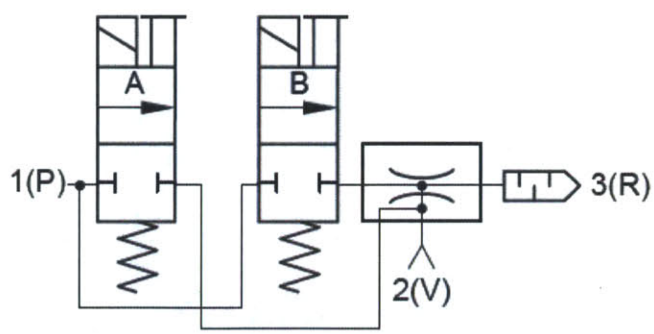


Figure 5-5: Pneumatic schematic of the VAD-M-I vacuum generator . When solenoid A is energized, there is compressed air at port 2 and vacuum when solenoid B is energized[33]

These vacuum generators have 2 control valves to allow for fast release of parts. When the solenoid in valve B is energized, compressed air flows from supply port 1(P) and out 3(R), creating a vacuum at suction port 2(V). When the solenoid in B is de-energized and the solenoid in A is energized, the vacuum stops and compressed air is redirected to 2(V). , quickly releasing the parts being held [33].

5.2.2 Pneumatic rotary actuators

Pneumatic rotary actuators are used in both sorting and insertion machines. These rotate 180 degree back and forth when the solenoid is energized and de-energized respectively. In the insertion machine, it is used to re-orient pins. This actuator also has a vacuum generator similar to the VAD-M-I described earlier, which helps in sucking pins onto the actuator (using vacuum) and blowing them back onto the sorting wheel (using compressed air). The 180 degree swinging of the insertion arm is also accomplished using a pneumatic rotary actuator.

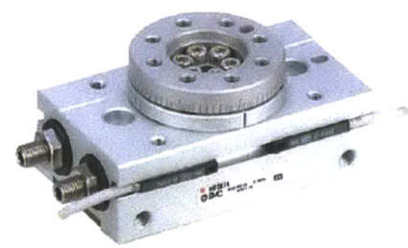


Figure 5-6: SMC Pneumatic rotary actuator [35]

The operation principle of a rotary actuator has been described in Figure 5-7

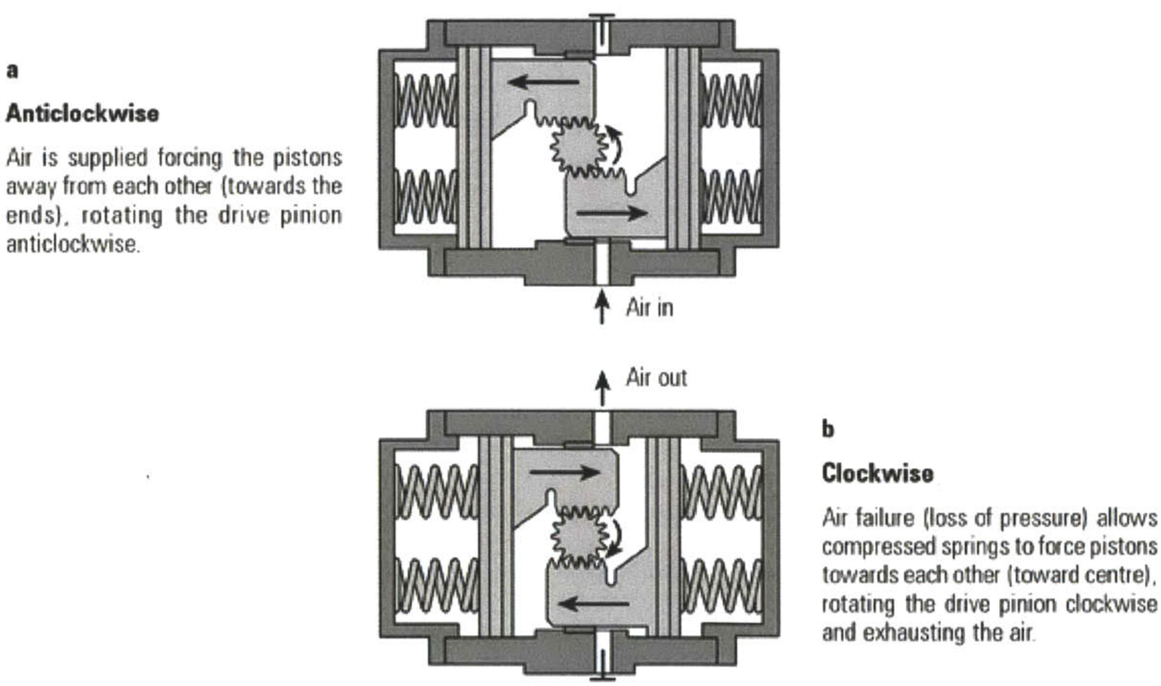


Figure 5-7: Operation principle of a rotary actuator [36]

5.2.3 Stepper Motors

Closed loop stepper motors were used to index:

1. Hollow rotary actuator for the pin sorting mechanism

2. Rotating drum to transfer pins from magazine to base of the magazine mount in the pin insertion mechanism

Oriental Motors DG-130 series rotary actuator featuring a hollow output table, as seen in Figure 5-8 was used for the pin sorting mechanism. It consists of a closed loop stepper motor attached to a hollow output table. The rotating wheel onto which pins are loaded from the vibratory bowl feeder[2], is attached to this table.

Figure 5-8: Oriental DG-130 Motors Hollow Rotary Actuator with a stepper motor and the drive[37]

As seen in Figure 5-9, the stepper motor is connected to the output table by a pinion and gear mechanism. The shaft of the stepper has a pinion attached to it, which mates with the gear on the output table. The gear reduction mechanism employs precision gears along with a proprietary adjustment mechanism that eliminates backlash. The positioning accuracy for the DG-130 series motor is $\pm$ 15 seconds[37]. The gear ratio for the DG-130 series hollow rotary actuator is 18:1.

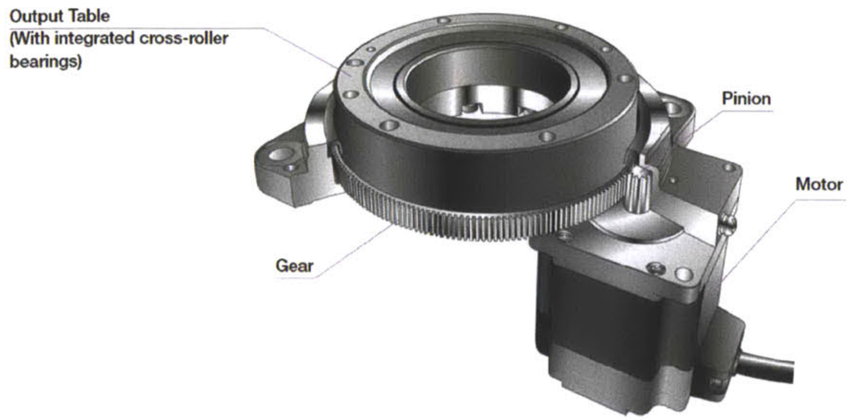


Figure 5-9: Pinion and gear based power transfer mechanism from the stepper motor to the output table [37]

5.2.4 Programming the stepper motor

A stepper motor needs electric signals to be sent to it from a power source. Typically, a stepper module is used in PLCs to accomplish this. Stepper motors are specified in terms of their resolution and torque. The resolution of a stepper motor refers to the number of pulses required for one complete rotation. For the DG-130 series motor, resolutions of 500, 1000, 5000 and 10000 pulses/rotation are available. Higher the resolution, smoother is the motion of the stepper. As mentioned earlier, the gear ratio on the output table is 18:1, thereby giving the entire system a resolution of 180,000 pulses/revolution. In other words, the output table rotates 0.002 degree per pulse sent from the PLC. Since, the sorting wheel has 6 stations [2], the stepper has to make 60 degree rotations. This translates to 30,000 steps for 60 degree rotation.

Calculating the maximum number of steps/sec

The maximum speed of the output table = 200 rpm

Gear Ratio = 18:1

Maximum allowable speed of the stepper motor,

$$\begin{aligned} & 200 \times 18 \\ & = 3600\ rpm \end{aligned} \tag{5.1}$$

At a resolution of 180,000 pulses/rotation, maximum steps per second,

$$\begin{aligned} &\frac{180,000 \times 3600}{60} \\ &= 10,080,000 \ \mathit{steps/sec} \end{aligned} \tag{5.2}$$

Hence, the stepper motor can be programmed to run at a maximum speed of 10,080,000 steps/sec. But for the sorting machine, the stepper was run at much lower speeds.

5.2.5 Machine Vision System

A Keyence XG-7502P machine vision system was used to identify the right pin type and also the orientation.

Figure 5-10: Keyence XG-7502P Machine Vision System [18]

Chapter 6 describes in detail the components used and the application development on the Keyence vision system.

5.2.6 Programmable Logic Controller

Two Blue Fusion 5220 PLCs from Control Technology Corporation were used, one each to control the pin sorting and pin insertion mechanisms. Both had stepper motor modules and sourcing type digital I/O. The stepper modules that were used send out 5V DC pulses to the stepper. Sourcing type inputs were used since all the sensors used in the machine were also sourcing type. Sourcing outputs, when switched on, give out either 5V or 24V DC, depending on the specifications. 24V DC sourcing outputs were used to energize the solenoids in the pneumatic valves. An I/O expansion rack was added to the PLC controlling the pin sorting process to accommodate all the inputs and outputs required for the system.

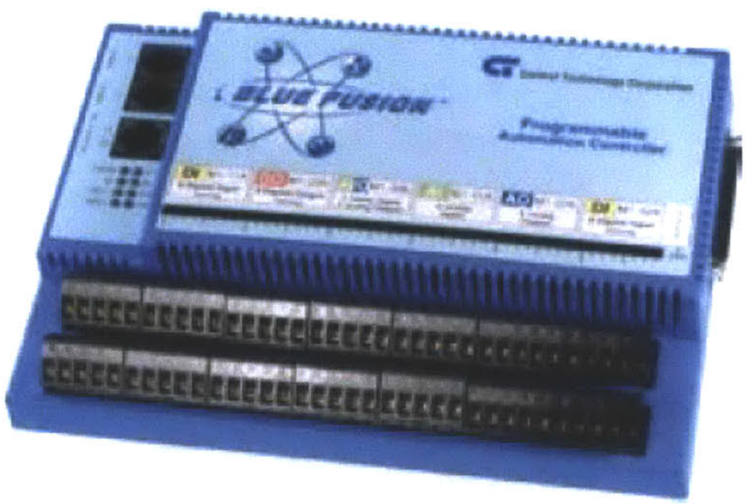


Figure 5-11: Control Technology Corporation Blue Fusion 5220 Controller

5.2.7 Other Components

Some of the other components of the control system include:

1. Proximity switches attached to the rotary actuator used to swing the pin insertion

2. Vacuum sensor to detect pin in the insertion head

3. Homing sensor attached to the hollow rotary indexer used in pin sorting

5.3 Integrating Machine Vision into the System

A Keyence XG-7502P system was used to check for the right pin type and also the orientation. The programming of the vision system has been dealt with in detail in Chapter 6.

A digital output on the PLC is used to trigger the camera externally every time the rotary indexer rotates by 60 degrees. The wiring diagram is as follows:

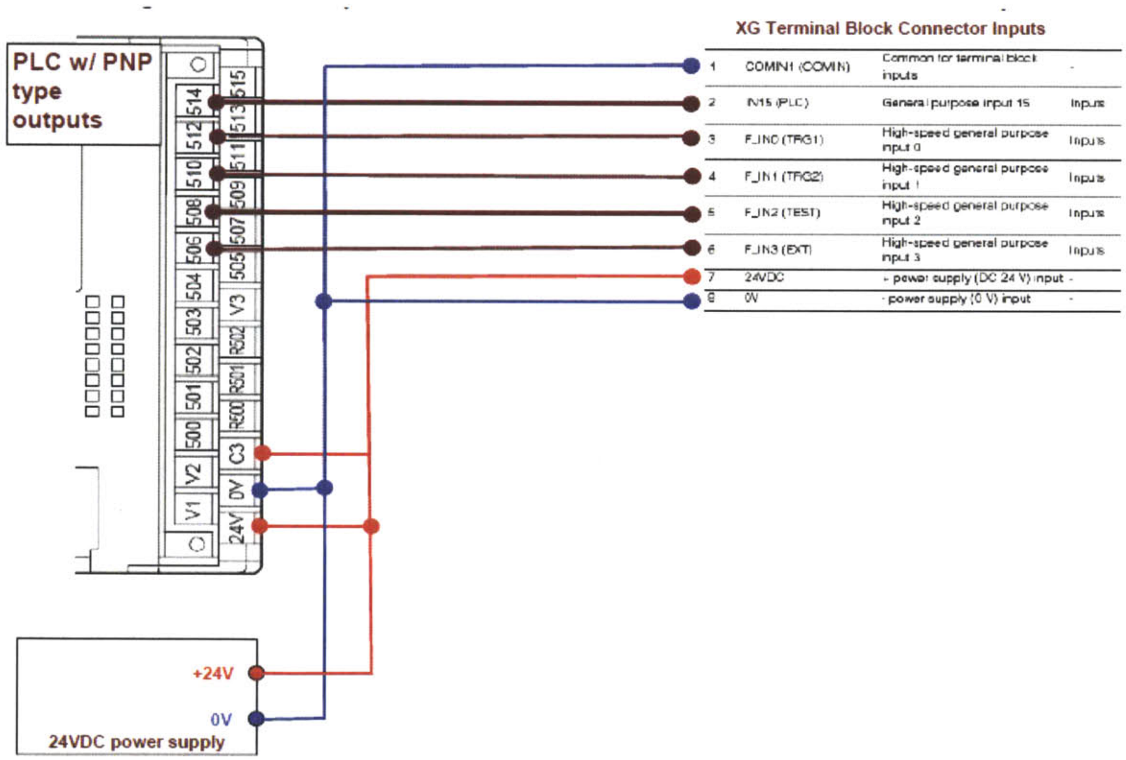


Figure 5-12: Wiring diagram to connect the Keyence system to the CTC controler to enable external camera triggering [18]

A common 24V DC output is used to power the PLC and the vision system. In a PNP circuit, the circuit commons are tied to ground. As shown in the figure, the 0V output of the power supply is connected to the terminal block input common. One of the digital outputs from the PLC is wired to the trigger input (F_IN0) of the terminal block.

The wiring diagram to connect the outputs from the vision system to the PLC is as follows:

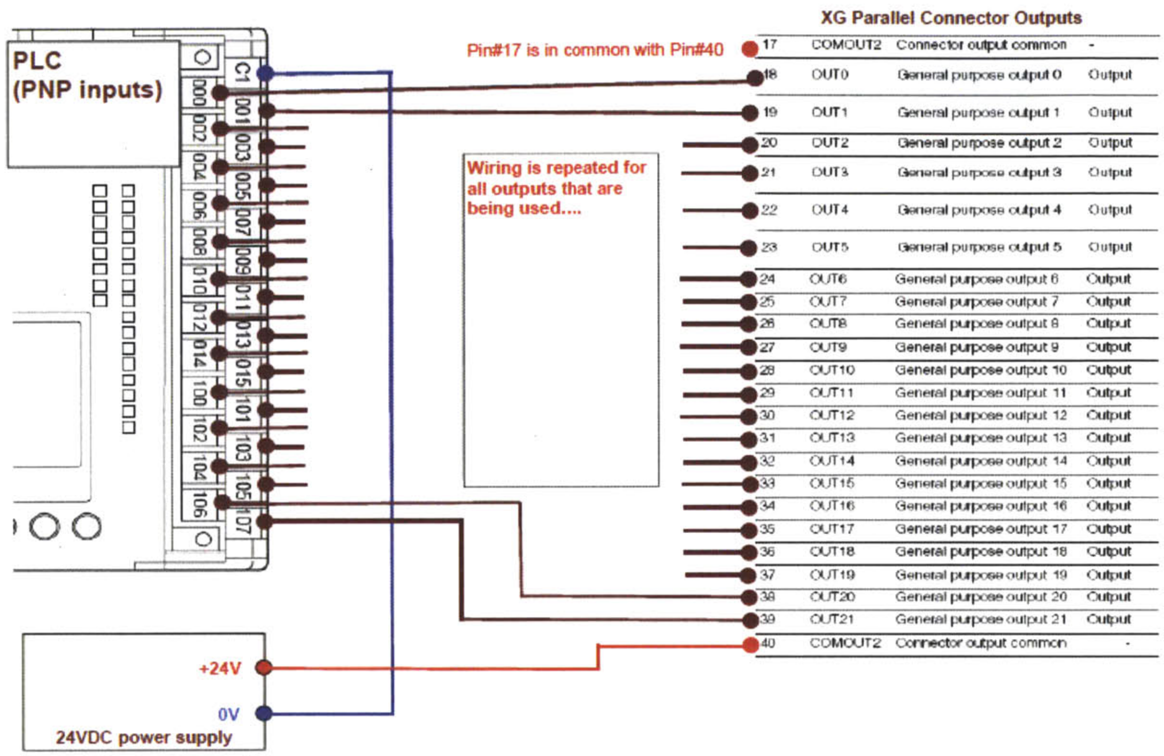


Figure 5-13: Wiring diagram to connect the Keyence system to the CTC controller to obtain the results from the Keyence system [18]

The positive (24V) terminal of the power supply is connected to the input common of the terminal block and the 0V output terminal is wired into the output common of the PLC. The digital outputs from the vision system are wired to the digital inputs of the PLC. In this case, 3 digital outputs were used. These outputs correspond to the right pin-right orientation, right pin-wrong orientation and wrong pin outputs.

5.4 PLC Programming

The CTC Blue Fusion 5220 uses a proprietary programming language called Quickstep. The overall format of a Quickstep program consists of a sequence of events, described as a series of program steps. Each step is a collection of instructions that determines the state of an automated machine or system for an interval of time. A step can contain both instructions which initiate motions and instructions that monitor various sensors. Steps can also contain specific high-level instructions for functions such as stepping motor and servo control [38].

5.4.1 Problems with QuickStep Programming Language

Quickstep 2.3 has a lot of issues that can make programming tedious and time consuming. The lack of some of the commonly used features in other programming languages increases the length of the program, which can sometimes make it hard to debug. Some of the shortcomings are:

1. Does not support arrays: It does have a data table though. But the real-time change in values cannot be seen while the program is being executed.

2. No IF-THEN statement: The lack of an IF-THEN statement makes it impossible to have simple conditional statements. The IF-GOTO syntax which is supported by Quickstep, makes it mandatory to have additional 'GOTO steps' each time this statement is used.

3. No FOR and WHILE loops: Quickstep doesn't support the most commonly used loops in programming. One has to resort to IF-GOTO statements for looping.

4. No built-in timer: A built-in timer is essential for measuring cycle time of various operations. Owing to the lack of this feature, an external timer has to be used for measuring process/cycle time.

5. No option of millisecond delay time in registers: Delay times for most pneumatic devices are set in milliseconds. QuickStep accepts millisecond delay time when it is mentioned directly in the program. But when a delay time is set in a register, only seconds and one-tenth of a second delay times can be specified.

6. Cannot create functions and subroutines: Functions and subroutines can be invoked every time a repetitive task needs to be performed. Quickstep does not

have this feature, making it mandatory to write tasks multiple times whenever they need to be performed, thereby increasing the number of steps..

7. Does not have in-built library for common mathematical operations: Common mathematical functions like square root, modulus, round off to the nearest integer, among others are missing.

5.4.2 Pin Sorting

Figure 5-14 shows the overview of the connections in the pin sorting process. The PLC is powered by a 24V DC supply. Sixteen digital outputs on the PLC are used to energize the solenoids in the pneumatic valves and 1 to trigger the camera. The 3 outputs from the camera are connected to the digital inputs of the PLC.

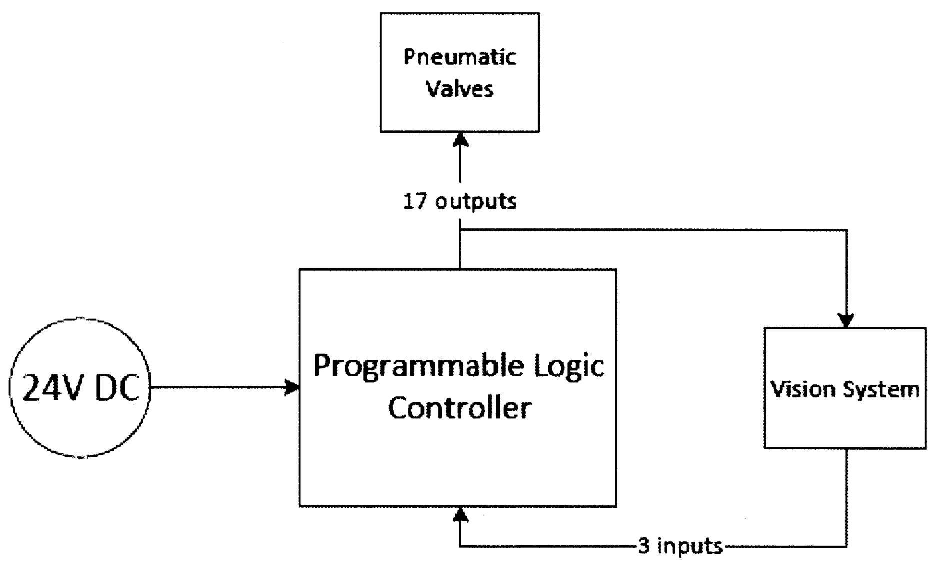


Figure 5-14: Overview of the connections in the pin sorting program

The pin sorting process involves loading of individual pins onto a rotary indexing unit from a vibratory bowl feeder. The pins are held in their slots by vacuum generators which are activated by energizing solenoids attached to them. The rotary indexer has 6 slots for pins and on every indexing of 60 degrees, a pin moves from one station to the other. The 6 stations are:[2]

1. Pin loading (from vibratory bowl) station
2. Dummy station
3. Camera station
4. Re-orienting Station
5. Magazine delivery station
6. Pin reject station

Figure 5-15 illustrates the vibratory bowl feeder, rotary indexer and the 6 stations.

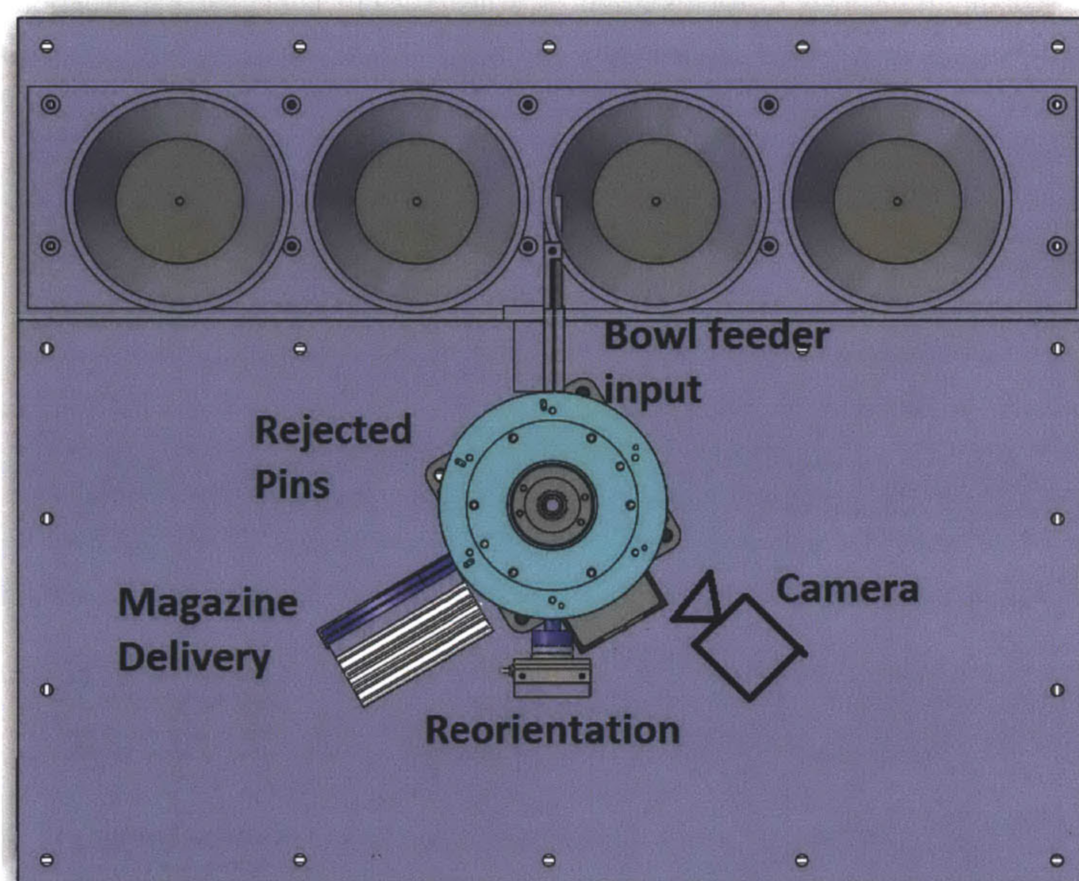


Figure 5-15: Top view of the pin sorting mechanism. The pins are loaded onto the rotating wheel from the bowl feeder at Station 1. The wheel rotates in the clockwise direction. The camera is at Station 3. Depending on the output from the camera, the pins get re-oriented, loaded into a magazine or rejected from the system

Stations are numbered 1 to 6 in a clockwise manner starting with the Pin Loading Station. The pneumatic valves at each of the 6 stations at the beginning is designated the same number as that of the station. Hence, in the program, the valve at the Pin loading station is called Valve 1 and its solenoid as Solenoid 1. A counter that updates itself on every indexing of the rotary wheel stores the present location of each solenoid. Thus on the first 60 degree turn, the counter stores that valve 1 (and hence solenoid 1) is at Station 2 and so on. This is used to energize and de-energize solenoids later in the program.

The PLC is programmed to send a 24V DC digital output signal to the rotary actuator to rotate by 60 degrees. Once this is done, a series of multi tasking steps are processed simultaneously at each station. A schematic of the pin sorting program is shown in Figure 5-16. The parallel steps occurring at each station are as follows:

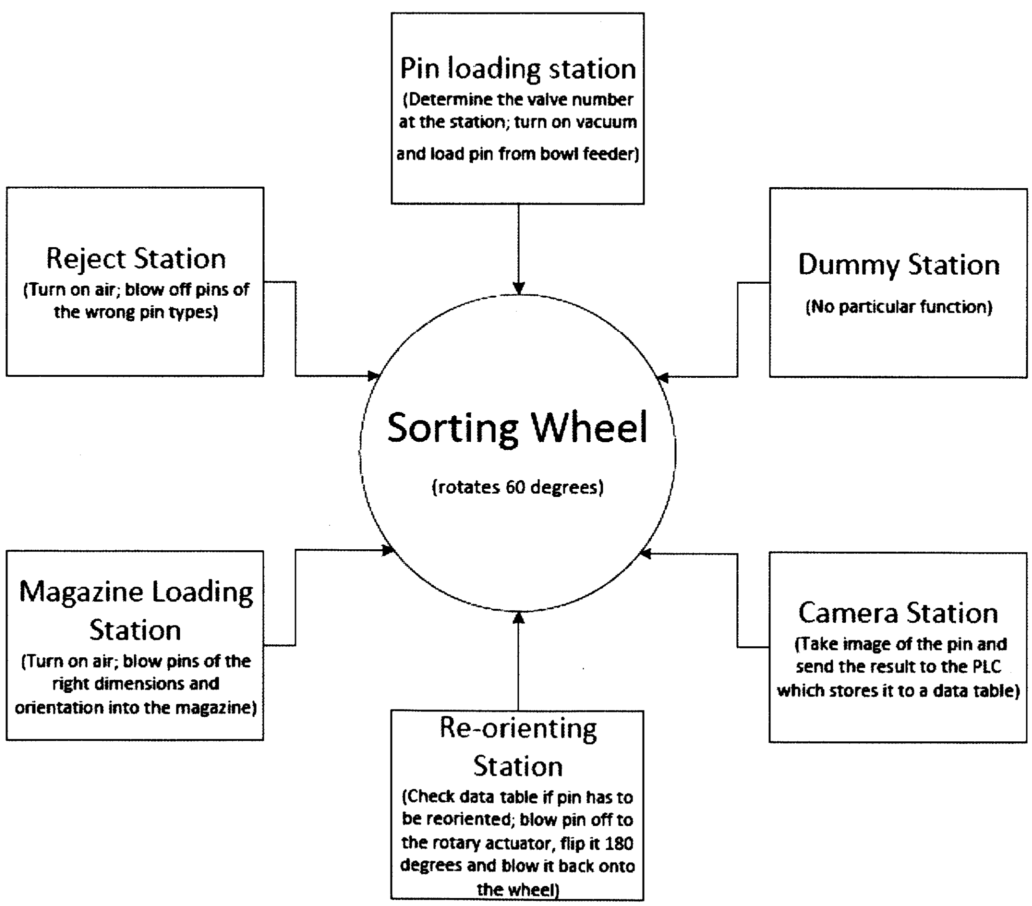


Figure 5-16: Schematic of the pin sorting program

Pin Loading Station

The program checks the counter for the solenoid number at the Pin Loading Station. This solenoid is then energized by the digital output from the PLC. A pin gets sucked from the vibratory bowl feeder onto the rotating wheel.

Dummy Station

There is no specific function for this station. This station is present due to non availability of a rotary indexer with 5 stations.

Camera Station

The camera captures an image of the pin presented to it. There can be 3 outputs from the camera:

1. Right pin in the right orientation
2. Right pin in the wrong orientation
3. Wrong pin

Depending on the result, it sends a digital output to the PLC (discussed in detail in the next chapter). There is a Data Table in the memory of the PLC that stores the station number where a particular pin is to be released. The data table has 6 rows, one for each solenoid and a column to store the release station. For instance, if the pin presented to the camera is being held by Valve 2, and it turns out to be the wrong pin type, the program stores 6 (as Station 6 is the pin reject station)for this valve.

The PLC has a dedicated register (register 126)to point at data table rows. One can access the columns in a specific row by storing the row number in this register. Data in the columns can be modified by accessing the columns by their names.

Re-orienting Station

The program accesses the data table to check if the pin at this station is supposed to be re-oriented or not. If so, the solenoid associated with this valve is de-energized, the

Table 5.1: A typical data table

Valve No.	Pin Release Station
1	5
2	5
3	4
4	6
5	5
6	4

pin is re-oriented and loaded back into the wheel. The re-orienting mechanism uses a 180 degree rotary actuator, which flips the pin to the right orientation. When the program detects that the pin in this station has to be re-oriented, the PLC energizes the vacuum generator on the rotary actuator, while turning on compressed air on the valve that is present at the re-orienting station. Then the actuator flips the pin 180 degrees, after which compressed air is turned on, on the actuator. Simultaneously, vacuum is turned on, on the valve present at the station enabling the re-oriented pin to be sucked back onto the wheel. Once the re-oriented pin is loaded back onto the wheel, the data table entry for this pin is updated from 4 to 5, thereby letting the PLC know that the pin should be loaded into the magazine.

Magazine Delivery Station

The right pins are loaded into the magazine. Here too, the data table is accessed to confirm if the solenoid has to be turned off or not. Compressed air is turned on to blow the pin into the magazine.

Pin reject Station

The wrong pin types are rejected from the system at this station by turning on compressed air.

For more details on the rotary indexing and the re-orienting mechanism, refer to Chang [2].

5.4.3 Pin Insertion

The existing PMJ machine at SynQor has an efficient mechanism in place to locate the holes in the PCB and insert a pin, once it has reached the insertion head. Hence, the pin insertion part of the developed prototype was restricted to loading the pin from the magazine and getting it successfully to the insertion head. The plan is to incorporate the insertion mechanism of the PMJ machine into the prototype developed in the future.

The control system for the pin insertion process consists of a PLC, pneumatic valves, 2 vacuum sensors to detect if a pin has been sucked in or not and proximity switches to detect the completion of the arm swing. The connection schematic is as shown in Figure 5-17

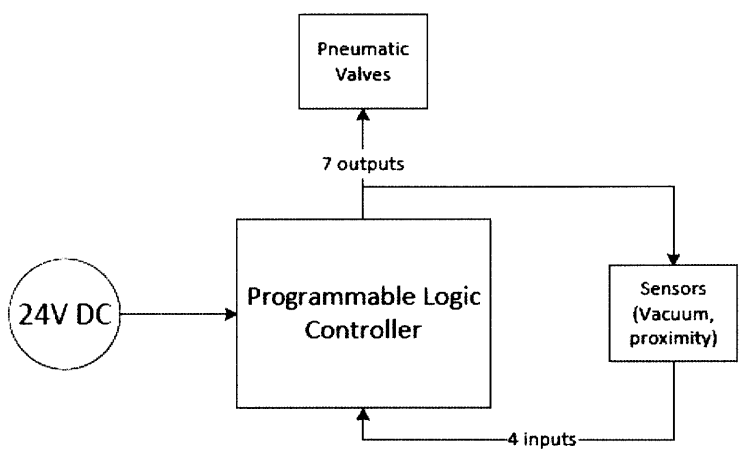


Figure 5-17: Overview of the connections of the pin sorting machine

The insertion arm is connected to a rotary actuator. One end of the insertion arm sucks in a pin from the magazine while the other end is inserting a pin. Once these tasks are completed, the arm rotates 180 degrees. This process continues till all pins have been inserted.

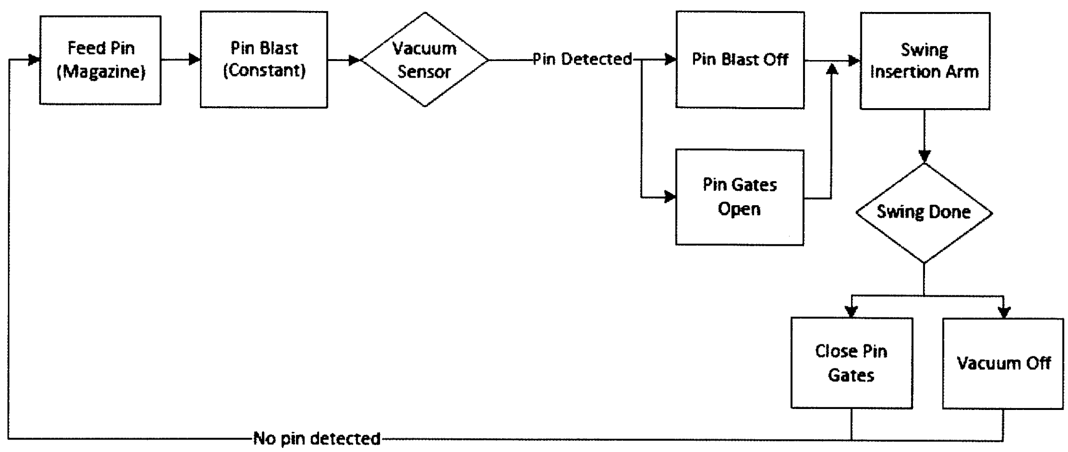


Figure 5-18: Flowchart of the pin insertion program

The program begins with energizing the solenoid for the main air flow line. A double acting cylinder is used to load pins from the magazine to the insertion head. This double acting cylinder is controlled by solenoid S7. For more details on how the pin is transferred from the magazine to the insertion tube, refer to Cook [3].

The pin is blown by a blast of air by energizing solenoid S5. The vacuum at the ends of the insertion arm pulls this pin into the insertion arm. The vacuum required to suck a pin is provided by 2 vacuum generators, S4 and S6. S6 is connected to end A of the insertion arm and S4 to end B. There is a vacuum sensor attached to each end of the insertion arm. The program monitors these vacuum sensors and only when these sensors detect a pin, will the insertion arm swing. In case, there is no pin detected, the program extends the cylinder again to load a pin into the insertion head.

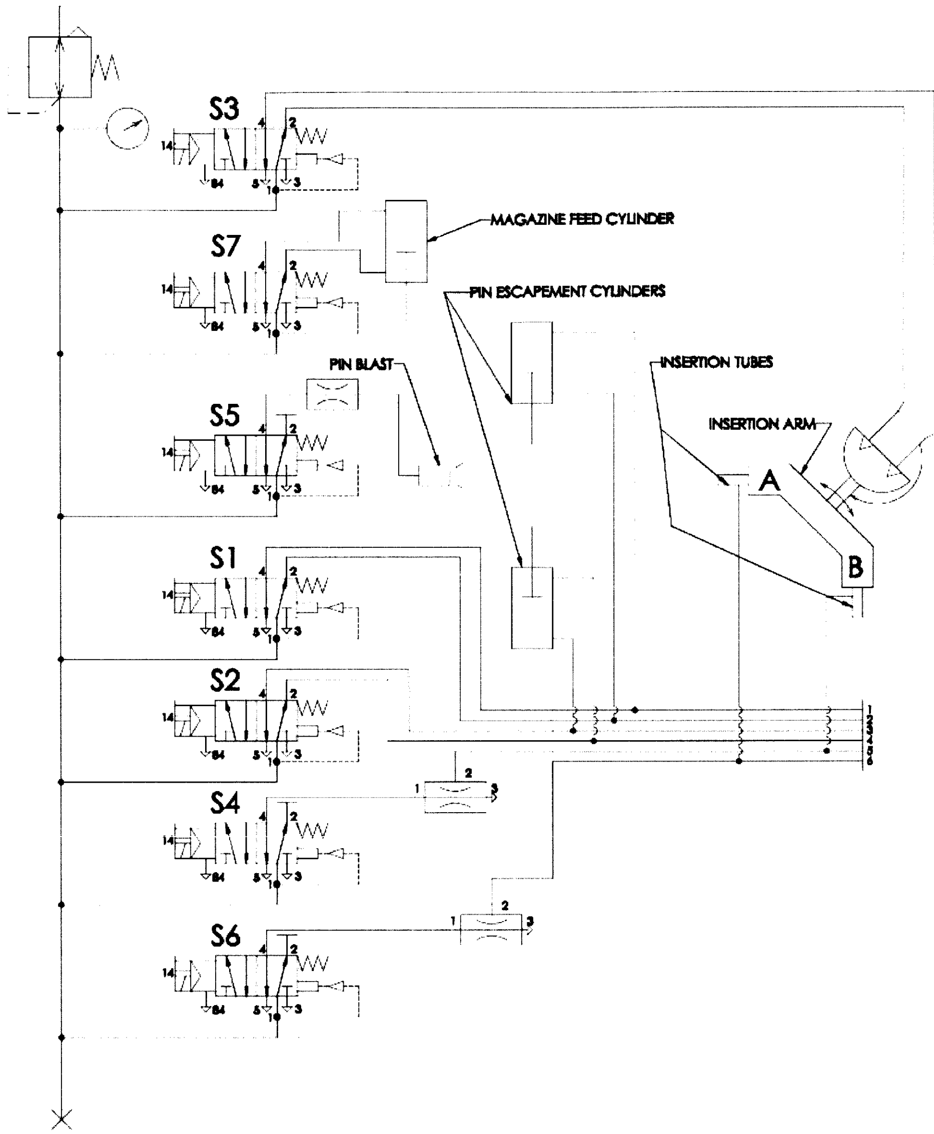


Figure 5-19: Pneumatic schematic of the pin insertion process[3]

A register has been used to detect which of the 2 vacuum generators is to be turned on for the insertion tube. The register stores 2 values, 1 or 2. The 2 tubes on the insertion arm have been named A and B respectively. The process starts with 1 being stored in the register, indicating vacuum generator on end A has to be turned on. The insertion arm then swings with the help of the rotary actuator, which is controlled by solenoid S3. Once this pin has been inserted, the value 2 is stored in the register, causing vacuum on end B to be turned on.

In the present prototype, once the arm has swung, the vacuum is turned off to drop the pin from the insertion tube, to symbolize pin insertion.

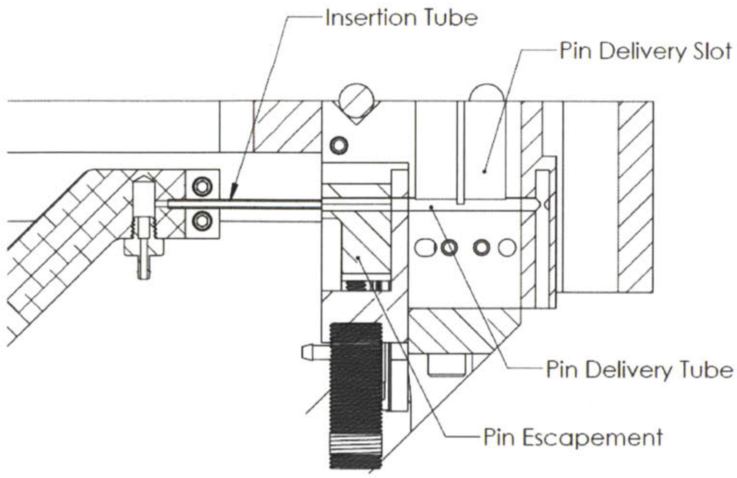


Figure 5-20: Section view showing how the pin escapement extends from the pin delivery tube to the insertion tube [3]

There are 2 pin escapements which are connected to double acting cylinders controlled by solenoids S1 and S2. Energizing the solenoids causes the gates to open.

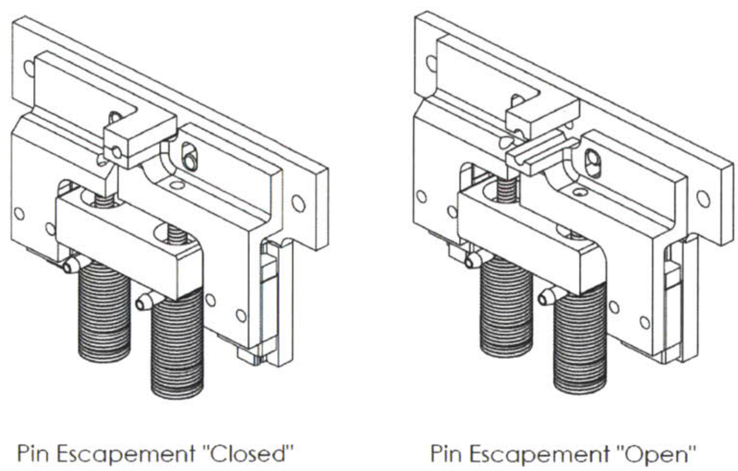


Figure 5-21: Section view showing how the pin escapement extends from the pin delivery tube to the insertion tube [3]

The insertion arm, whose motion is controlled by the rotary actuator, then swings 180 degrees. The process repeats until all pins are inserted.

Setting delay times for each of these steps is an important part of the programming. These delay times allow for building up of pressure in the valves, for mechanical motions to come to rest before the next motion begins and so on. Delay time setting has been described with in detail in Chapter 7.

Two programs were written for the pin insertion machine. The first one was a multitasking program in which a pin is loaded into one of the insertion tubes while the other is inserting a pin into the PCB. The second one was a program where the tasks happen in a sequential order. Both programs performed well, but for setting delay times and calculating cycle time, the serial program was used.

In the final machine that will be part of the production line, the program will send an output to the robotic controller to locate the X and Y co-ordinates of the hole where the pin is to be inserted. Once the hole is located, insertion head will drive the Z axis down to insert the pin and the Z axis is retracted. The robotic controller then sends a signal to the PLC that the insertion process is complete. The process of a pin being sucked into the other end of the insertion arm happens in parallel with the insertion process.

Chapter 6

Machine Vision Application Development

6.1 Existing System

6.1.1 Festo Checkbox Camera

The PMJ machine uses a Festo Checkbox CHB line scan camera to capture images of the pins as they move along a conveyor. Components are scanned as they pass through the optical channel of the camera. The Checkbox CHB consists of a housing which comprises all the necessary components. A mixture of any number of parts as well as objects of considerable length (upto 1000 mm) can be recognized and processed without the need to observe minimum distances. [39].

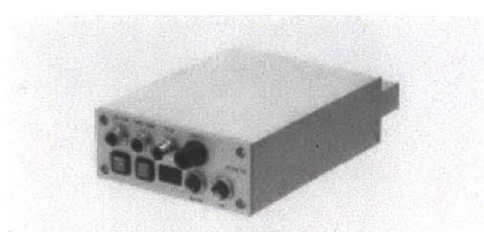


Figure 6-1: Fest CHB Checkbox camera

6.1.2 Problems with the Checkbox System

The Checkbox camera is not meant to image and measure the dimensions of objects as small as the pins used in this project, especially the diameter. This system is not capable of producing good quality images of the pins and hence measuring critical dimensions is an issue, thereby allowing wrong pin types to get past the system. In the existing PMJ system, the pins moved about the collar on the conveyor and this movement of the pins produced distorted images of the pins, making it hard to measure critical dimensions. Also, since the image quality was poor, it was hard to discern the top part from the bottom part of the pin, allowing pins in the wrong orientation to pass through the system.

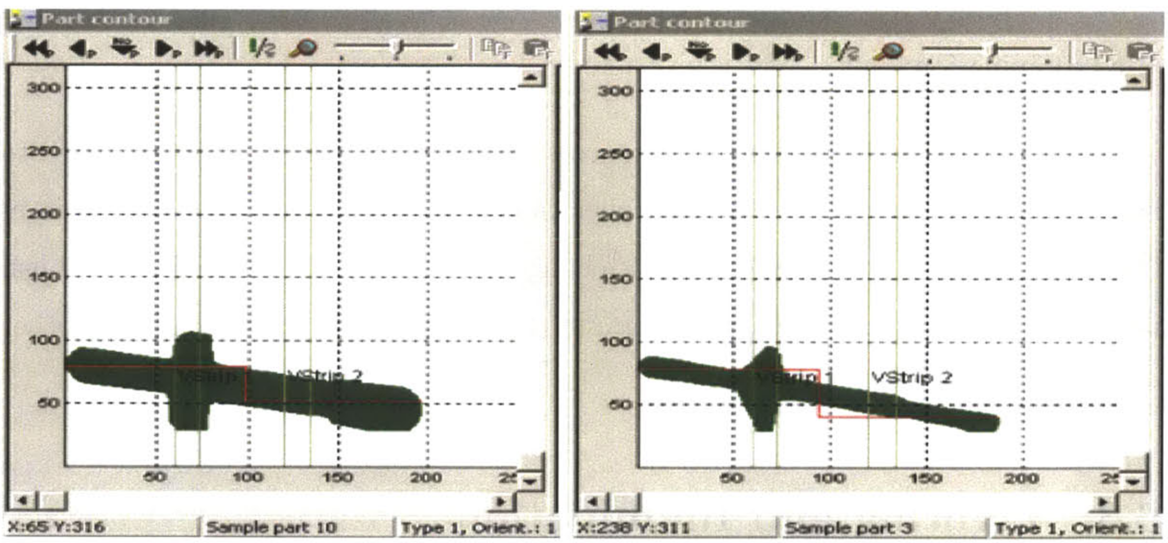


Figure 6-2: Two images of a 0.040" pin captured by the Checkbox at 2 different instances

6.2 Requirements of a Vision System

An efficient vision system used in the pinning process must meet the following requirements:

1. Image capturing and processing speed not higher than 500ms/pin (smaller preferable)

2. Serial or Ethernet port for communications

3. Robust and reliable (high Mean Time Between Failures)

4. Hardware handshaking I/O for rapid communication of results and settings.

5. Reasonably priced

Based on these requirements, a Keyence XG-7502P machine vision was purchased. The main components of the system were:

1. Two megapixel camera

2. Dual core processing unit capable of handling 4 cameras simulatenously

3. Illumination Unit

The XG-7000 Series uses a 2-way process (either on the controller or on a PC) to build inspection programs. The controller can be used to carry out adjustments in the field, addition of units and product changeovers. A PC can be used to establish inspection methods and build new programs with original operation menus and other essential GUI elements. [18]

6.3 Lighting and Illumination

A lighting system for a machine vision system consists of front and back lighting.

6.3.1 Selection

The primary objective of the illumination unit was to enable the camera capture an image that shows the edges of the pins and the orientation clearly. Under normal circumstances, a back light is used to form an image that would show the edges clearly and a front light to capture the patterns facing the camera. But the pins are held onto the rotating wheel using pneumatic valves and hence is hard to illuminate the pins using a back light. Hence, the challenge was to adjust the intensity of the front

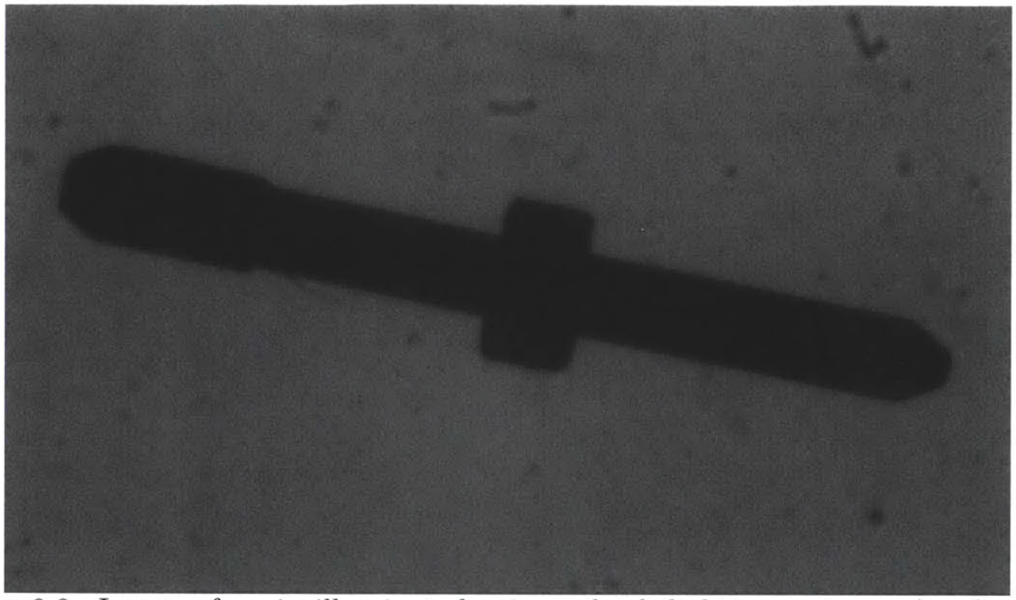
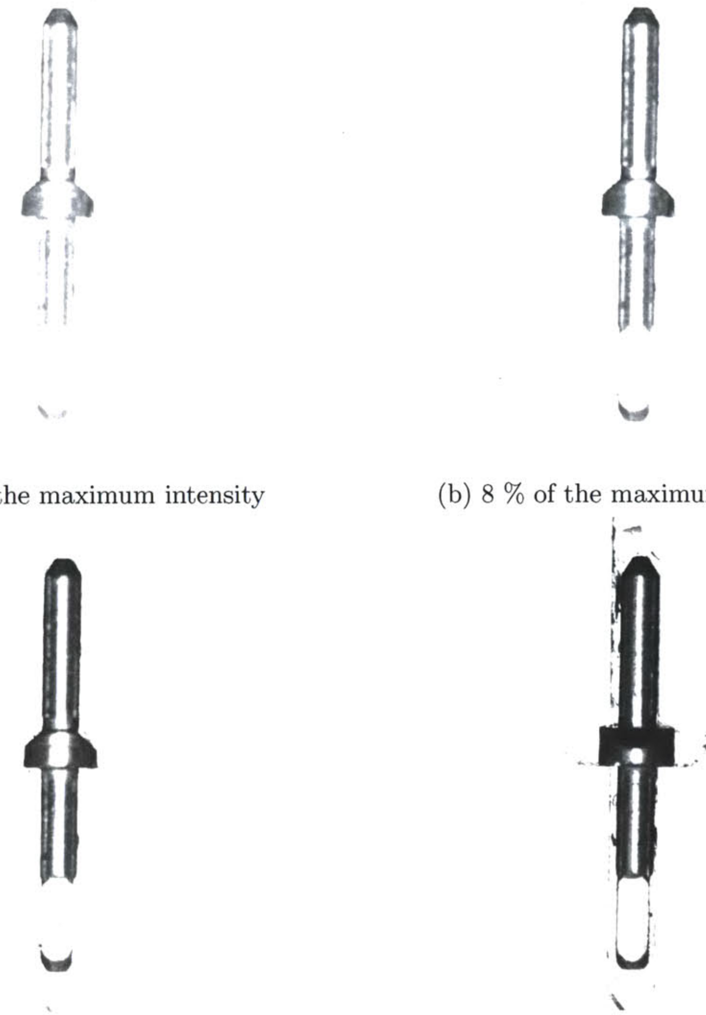


Figure 6-3: Image of a pin illuminated using a back lighting system. A columnate filter has been placed on the back lighting system

light in such a way that the edges are conspicuous enough. The following section deals with choosing the intensity of the front light.

6.3.2 Intensity

The Keyence vision system has the provision to vary the intensity of the lighting unit from 0 to 255, 255 being the brightest. It was found that an intensity greater than 40 resulted in s glaring image with the pin not being visible. The intensity was gradually reduced to a stage where all the edges were clearly identifiable. Figure 6-4 shows the change in image quality with decrease in intensity of the front light. Although, the image of the pin at 2% of the maximum intensity is the sharpest, edges of the recess are visible, which might interfere in edge detection. Hence, the lighting intensity was set to 4% of the maximum, where all edges are clearly visible without there being any 'noise'.



(a) 12 % of the maximum intensity

(b) 8 % of the maximum intensity

(c) 4 % of the maximum intensity

(d) 2 % of the maximum intensity

Figure 6-4: Images of a .040" diameter pin in the rotating wheel at different intensities. The best image is obtained at 4 % of the maximum intensity

6.3.3 Effect of Ambient Light

Ambient light plays an important role in the final image quality. It was found that the image quality significantly improved on shutting out ambient light. This was done by placing an opaque box over the camera and the pin fixture. On shutting out ambient light, it was found that the pin appeared darker with a bright background. This contrast is ideal to locate the edges of the pin. Figure 6-5 shows the change in image quality on changing from only ambient light (with the camera illumination turned off), to front lighting under ambient lighting and finally to shutting out ambient light. As can be seen in the figure, the image quality gets better, with there being an increased contrast between the image of the pin and the background.

(a) No lighting(ambient light)

(b) Front lighting with ambient light

(c) Front lighting with no ambient light

Figure 6-5: Images of a .040" diameter pin in the rotating wheel at different lighting conditions. It can be clearly seen that the best image was produced when front lighting was used in the absence of ambient light

6.3.4 Setting the shutter speed

The shutter speed of the camera can be set using the XG Vision Terminal software. The shutter speed can be varied from 0.05 ms (1/20,000 ms) to 66.67 ms (1/15 ms). The default value for this is 2 ms(1/500 ms). The ideal shutter speed under the given conditions was found to be 16.67 ms (1/60 ms).

6.4 Application Development

6.4.1 Unique identifiers of a Pin

SynQor Inc., presently has 24 pin types. But 3 features are adequate to uniquely identify a pin type. These are:

1. Total length of the pin
2. Length from the upper tip to the top edge of the collar, or bottom tip to the lower edge of the collar
3. Diameter of the pin

These 3 features can uniquely identify a pin type irrespective of whether the insertion end (bottom tip) has a hexagonal or square cross section. The vision application developed looks for the required edges to calculate these parameters.

6.4.2 Tools Used

Pattern Match

Pattern Match is used to check the orientation of the pin. The vision system is taught to look for the pattern similar to that of the top portion of the pin. If it detects the pattern, the pin is in the right orientation, else it is inverted and has to be re-oriented.

Edge Detection

Edge detection tool is used to detect the edges required to calculate the unique identifiers of a pin. This tool looks for a change in intensity within the region it is supposed to look for. As mentioned earlier in Section 6.3.2, the intensity of the front lighting used was adjusted in a manner so as to form a bright image of the rotating wheel with a dark image of the pin in the recess. This bright and dark contrast makes it easy to locate the edges of the pin.

Position Adjustment

Position Adjustment tool acts as a link between the Pattern Match and Edge Detection tools. Position Adjustment finds the geometric relationship between the locations of the pattern and the edges to be detected in the original reference image. Every time the system detects a pattern similar to the one it was 'taught' to look for in the captured image, it tries to detect the edges using the same geometric relationship between the pattern and edges in the reference image. Hence, position adjustment makes sure that edges are always located at fixed distances from the pattern, irrespective of where the pattern is located.

Branch and Join

Branch and Join are used to split a flowchart into 2 depending on the pass/fail of a condition.

Calculation

Calculation is used to perform basic arithmetic and logic calculations within the program. It has provisions for common loops like WHILE and IF-THEN. The user can set upper and lower limits for the calculated value. In the present program, the Calculation tool has been used to determine the dimensions of the pin from the co-ordinates of the edges.

Parallel Terminal Output

Parallel Terminal Output lets the user assign results of certain steps of the program to the output wires on the terminal block output.

6.4.3 Flowchart Design

Figures for pattern match, edge detection, calculation, right pin and wrong pin.

The vision software used in the Keyence system, Vision Terminal, uses a flowchart design to build applications. The user selects the required tools like Pattern Match, Edge Detection etc. in the order in which they should appear in the image processing application. Figure 6-6 shows the flowchart designed on Vision Terminal.

The flowchart begins with triggering the camera to capture the image of the pin which is presented to it. The triggering is done by the external PLC. Every time the rotary wheel advances 60 degrees, the PLC triggers the camera. The step that follows Capture is Pattern Search, which is trained to look for a pattern similar to the top portion of the pin (to the top of the collar)(figure). A pattern search can fail under 2 circumstances:

1. Pin presented to the camera is in the opposite orientation

2. No pin was loaded onto the rotary indexer.

The pass/fail limit for pattern match has been set to 94%. The percentage value of the pass/fail limit refers to the degree to which the pattern detected in the present image is similar to the one that the vision system is referencing with.

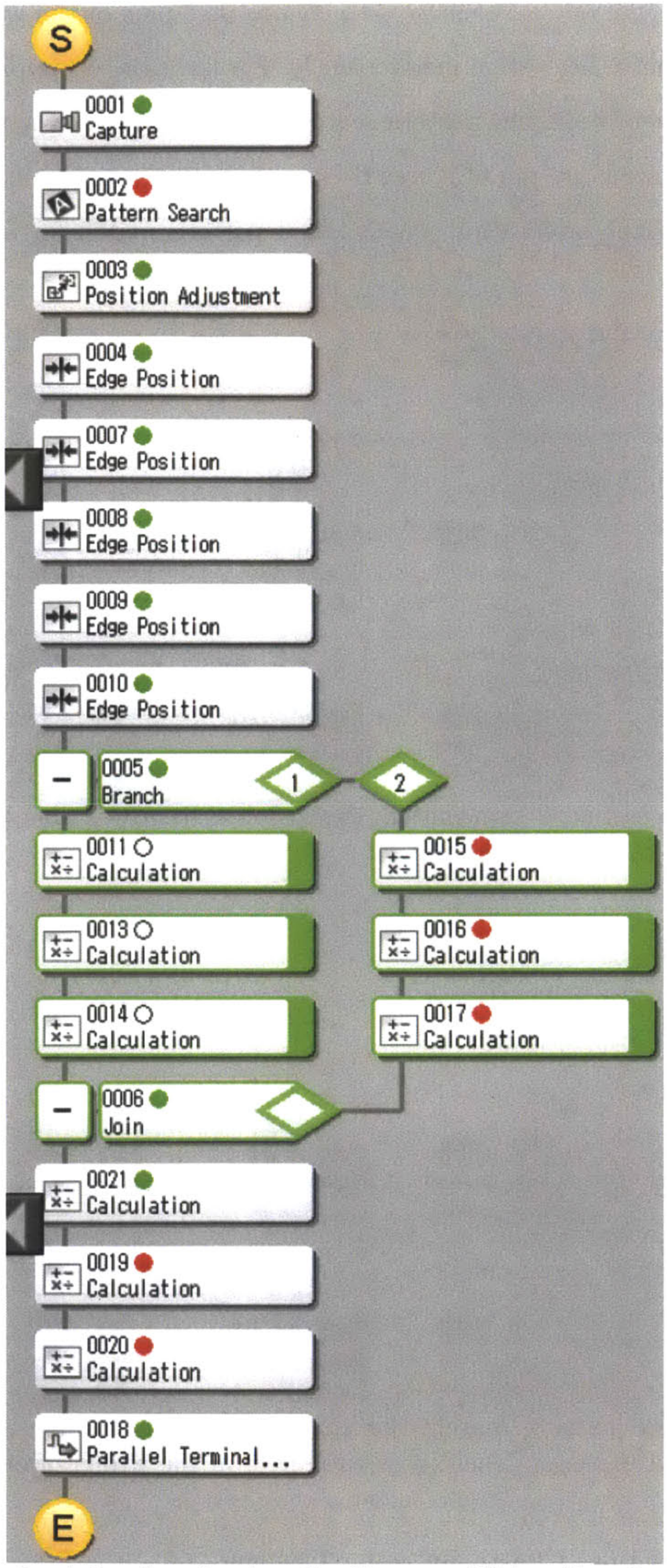


Figure 6-6: Flowchart developed using the Keyence Vision Terminal. Each block in the flowchart represents an image processing step

The high pass/fail cut off of 94% is to ensure that pins of the wrong orientation don't get passed onto the system inadvertently. For the case where pins are presented in the opposite orientation, the pattern search percentage lies in the range of 65-80%. It is 0 (zero) if there is no pin. Figures 6-7 and 6-8 show a successful pattern match for a pin in the right orientation and a failed pattern match for a pin that needs re-orientation.

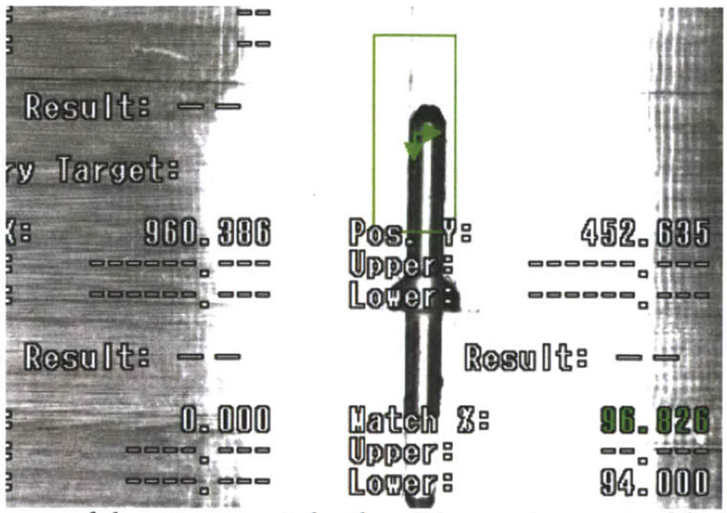


Figure 6-7: A successful pattern match; the vision system was able to find a pattern that matched the top part of the pin

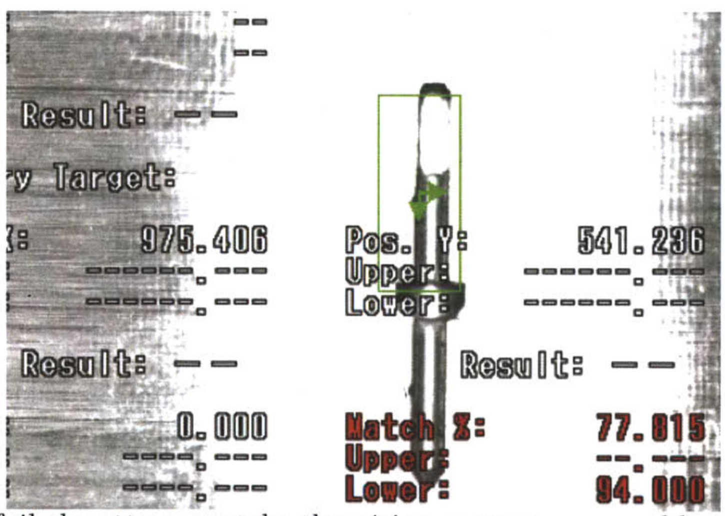
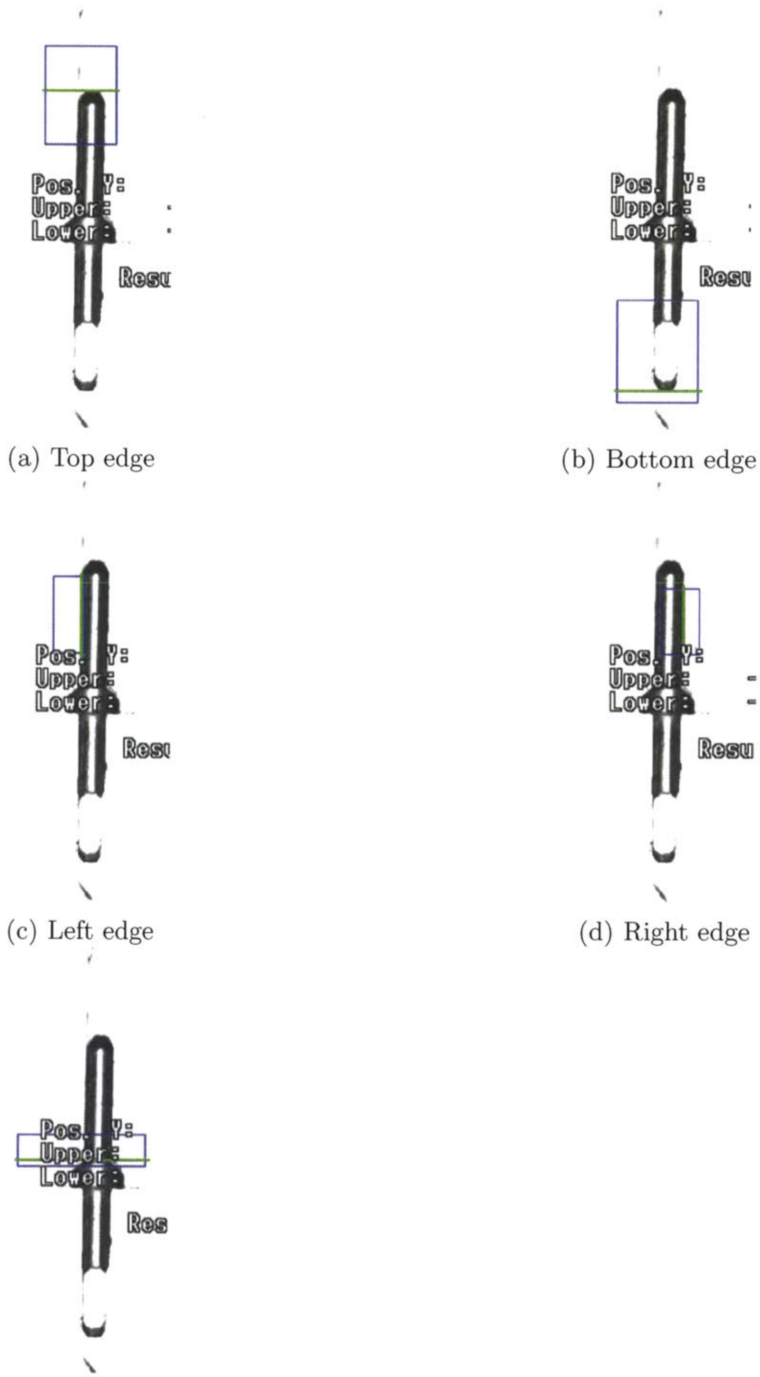


Figure 6-8: A failed pattern match; the vision system was unable to find a pattern that matched the top part of the pin as the pin is in the wrong orientation

Next is the Position Adjustment step. This step 'tells' the Edge Detection steps that follow, where to look for edges. Edge Detection tool is deployed to detect the top and bottom tips of the pin, the vertical edges and the upper edge of the collar. It must be noted that the upper edge of the collar could be either the top edge or the bottom edge of the collar depending on whether the pin is in the right orientation or not. Figure 6-2 shows the edges detected using the Edge Detection tool.



(a) Top edge

(b) Bottom edge

(c) Left edge

(d) Right edge

(e) Top edge of collar

Figure 6-9: Edge detection using the Keyence vision system

The flowchart then splits into 2 branches depending on the result of the pattern match step. Each branch has 3 Calculation steps.The control flows into the left branch if the pattern match was a success. In this branch, the Calculation steps determine the total length of the pin, diameter and distance from upper tip to the top edge of the collar are determined. On the other hand, the control flows into the right branch if the pattern match was a fail. In this case, the distance from the bottom tip (insertion end) to the lower edge of the collar is measured along with the diameter and length of the pin. Figure 6-9 shows the edges detected to calculate the 3 key identifiers of the pins.

The 2 branches join together after calculating the required parameters. It is followed by 3 more Calculation steps that determine the pin type and the orientation. Each step in the flowchart has a binary value associated with it. It is 0 (zero) if that particular step was a pass and 1 if it failed. The system assigns a default value of 0 if a particular step is not processed. Hence, the 3 Calculation steps in one of the branches that was not processed for a particular run has a default value of 0 associated with it.

The first Calculation step after the joining of the 2 branches calculates the sum of the binary values of the 6 Calculation steps in the 2 branches. If the answer is 0, it is the right pin, as it implies that all the required values were in the specified range and hence that particular step was a success. In case it is a non-zero value, one or more calculations are not within limits and hence, not the right pin. The upper and lower acceptable limits for this Calculation step is set as 1 and 6. In other words, this step is a pass if it is the wrong pin and fail if it the wrong pin. The underlying reason is that the output wire corresponding to this step on the Parallel Terminal will turn on if it is the wrong pin type and inform the PLC about it.

The second Calculation step checks if it is the right pin in the right orientation. An IF-THEN script is used to accomplish this.

IF (result of Calculation step no. is fail) AND (Pattern Match is success) THEN
ANS=0

ELSE

ANS=1

END IF

Hence, the above Calculation step is a pass if it is of the right pin type and in the right orientation.

The third Calculation step checks for right pin in the wrong orientation. An IF-THEN script is used to accomplish this.

IF (result of Calculation step no. is fail) AND (Pattern Match is fail) THEN

ANS=0

ELSE

ANS=1

END IF

The final step in the flowchart is the Parallel Terminal Output. This is used to communicate the result obtained from the vision system with the PLC. Each of the 3 final Calculation steps is associated with a unique wire on the I/O pigtail cable that runs from the output parallel terminal block of the vision system to the input terminal block of the PLC. Depending on the result, on of the 3 wires turns on, thereby letting the PLC know the pin type and the orientation.

Chapter 7

Testing and Results

7.1 Performance of the Machine Vision System

The machine vision application was tested by loading pins of the different lengths, but of the same diameter on the sorting wheel. The recess in sorting wheel could accommodate only pins of 0.040" diameter and hence pins of other diameters were not tested.

7.1.1 Setting Tolerances in the Vision Application

The Keyence vision software allows the user to set tolerances on measures dimensions. Most of the dimensions deviate from the expected values owing to:

1. Inherent tolerance in the dimensions
2. Slight deviation in the edge located by the vision system
3. External factors like vibration etc.

To set reasonable tolerance limits on the dimensions, 100 pins of the right type and right orientation were used. This pin type is the most commonly used pin at SynQor. These pins were loaded onto the sorting wheel and the 3 unique identifier dimensions along with the pattern match percentage were measured. Figures 7-1, 7-2 and 7-3 show the variation in the dimensions as measured by the vision system.

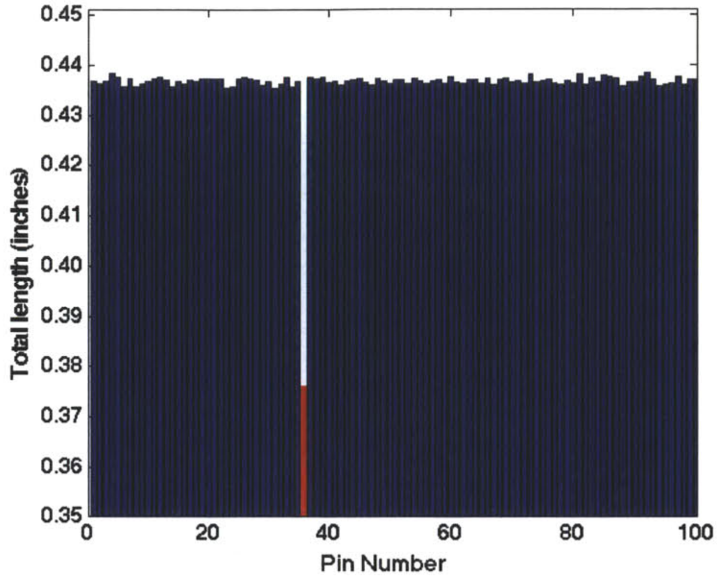


Figure 7-1: Variation in the total length of the most commonly used pin as measured by the vision system. The red bar indicates a failed measurement. The tolerance on the total length was set between 0.430 and 0.440 inches

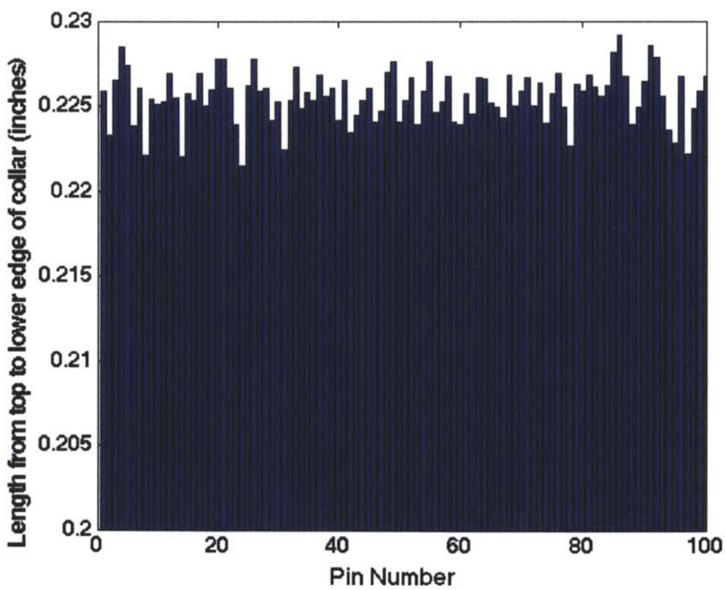


Figure 7-2: Variation in the length between the top edge and the lower edge of the collar the most commonly used pin as measured by the vision system. The red bar indicates a failed measurement. The tolerance on the total length was set between 0.220 and 0.230 inches

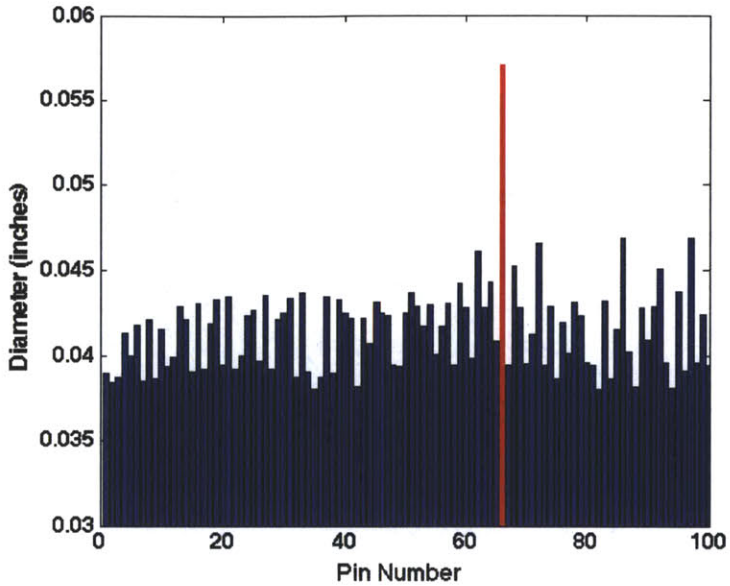


Figure 7-3: Variation in the diameter of the most commonly used pin as measured by the vision system. The red bar indicates a failed measurement. The tolerance on the total length was set between 0.035 and 0.045 inches

Based on the data, the following tolerances were set:

- Total length of the pin: 0.430 to 0.440 inches
- Distance from top to the lower edge of the collar: 0.220 and 0.230 inches
- Diameter of the pin: 0.035 to 0.045 inches

The actual values for the above parameters are 0.435, 0.225 and 0.40 inches. There is some tolerance on these values to account for variability in the manufacturing process. The tolerance set in the vision system is higher than the actual tolerance on the pins. As it can be seen, the tolerance on the diameter of the pin is about 25%, which is significantly higher than the tolerance set on the other parameters. There were instances when the system detected one of the edges of the recess as the edge of the pin, thereby introducing higher variability in the diameter values. Also, the recess used in the sorting wheel can accommodate only pins of 0.040" diameter and hence safe to have a slightly higher tolerance to lower the rejection rate of the right pins. In case of the 0.040" diameter pin being present in the sorting wheel meant for a pin of larger diameter, the edges of the recess will be farther away from the edges of th recess, making them discernible from one another. The next diameter of the pins that SynQor is well above the tolerance limit and hence there is no possibility of a wrong detection.

7.1.2 Robustness of the Pattern Match Tool

Next, the pattern match percentage of the pins were analyzed. The vacuum on the sorting wheel was turned on to hold the pins in place. The results revealed that some changes were required in the original vision application developed. The testing process revealed that the initial pattern match cut-off of 94 % was too high for the system. The efficiency of the system with this high pattern match cut-off was 60%. The efficiency increased to about 85% when the cut-off was lowered to 90%. An efficiency of 93% was obtained when the pattern match cut-off was further lowered to 86%. Figure 7-4 shows the variation in the pattern match percentage of the right pins in the right orientation.

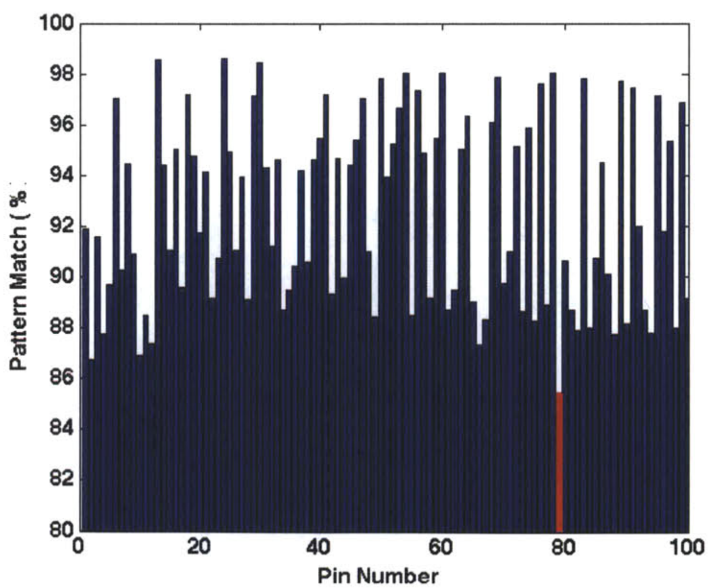


Figure 7-4: Variation in the pattern match percentage of the most commonly used pin as measured by the vision system. The red bar indicates a failed pattern measurement. The pattern match cut-off percentage was set to 86%

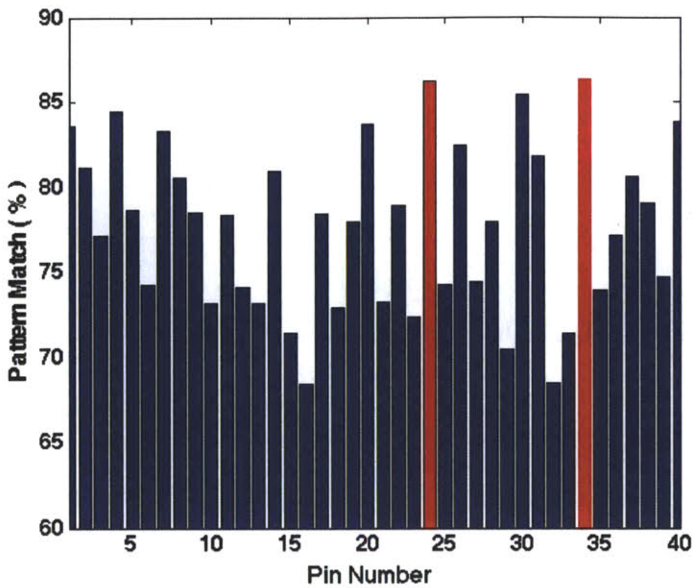


Figure 7-5: Variation in the pattern match percentage of the most commonly used pin in the inverted position as measured by the vision system. The red bar indicates a failed pattern measurement.14 of these had a pattern match percentage greater than 80; 2 passed.

The application was then tested using right pin types in the opposite orientation. But this revealed an alarmingly high pattern match. 14 out of the 40 pins tested had pattern matches higher than 80%, while 2 of these cleared the cut-off of 86%. Figure 7-5 shows the variation in the pattern match in the opposite direction.

Hence, pattern match is not a robust and reliable tool when it comes to identifying the orientation of these pins.

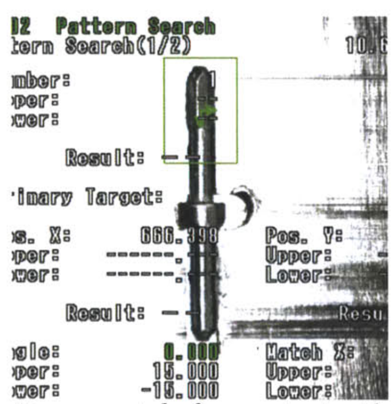


Figure 7-6: A successful pattern match for a pin in the opposite orientation. This pin is supposed to fail the pattern match test. The pattern match tool was not used in the application after obtaining such results on a repeated basis

The main reason for the failure of the pattern match tool is the use of vacuum to hold the pins in place. The initial application testing was done without vacuum. Under the absence of vacuum, pins tend to rest about their collar in the recess, under the action of gravity (as shown in 7-7). Hence, they are always in vertical position. But vacuum overcomes the force of gravity and pins no longer rest in a vertical position. Most of the pins were found to be oriented at an angle with the vertical, thereby making it hard for the vision system to successfully recognize a pattern. Since the pattern match cut-off was lowered to accommodate this effect, some of the pattern matches that were supposed to fail (wrongly oriented pins) cleared the cut-off, making it a less efficient tool in this context.

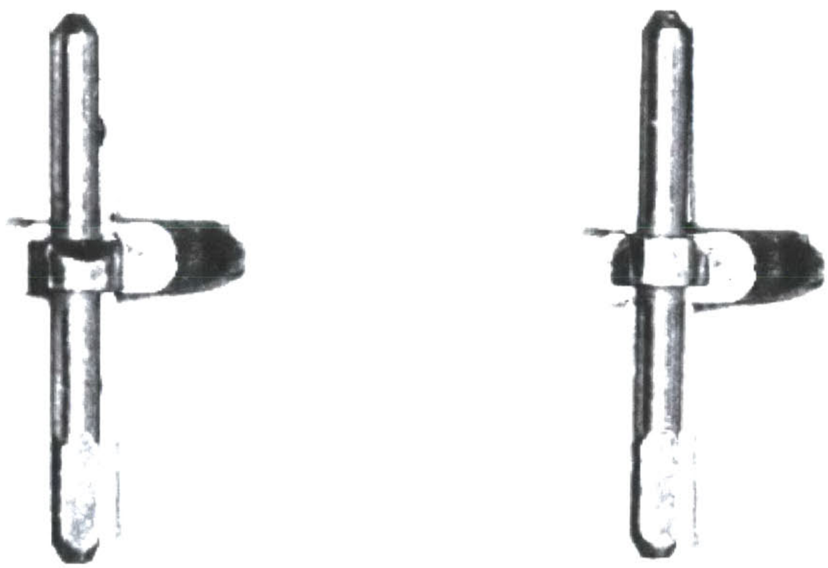


Figure 7-7: The position of the pins before and after turning on the vacuum. On turning the vacuum on, the pin raises from the collar and deviates from the vertical position

7.1.3 Problems with Edge Detection Tool

The measurements on the dimensions were then analyzed. The measurement of the total length and diameter of the pins were well within the acceptable range. But the distance from the top of the pin to the collar had a huge deviation from the expected range. A careful analysis of the images led to the conclusion that wrongly detected edges was the reason. In all cases where the dimension was out of acceptable range, the pins were not resting about their collar in the recess. This can again be attributed to the presence of vacuum. Most of the pins were found to be slightly raised above the slot in the recess where the collar usually rests when the vacuum is absent. This causes the vision system to detect the edge of the slot of the recess as the edge of the pin (as shown in Figure 7-8), which yields erroneous results.

Another reason for problems with the edge detection tool is the chamfer on the sorting wheel. The chamfer creates a shadow in the image, causing the system to identify the shadow as the edge.

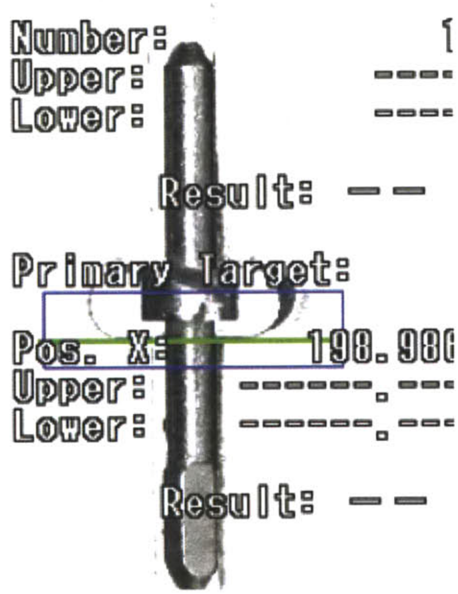


Figure 7-8: A successful pattern match; the vision system was able to find a pattern that matched the top part of the pin

This problem was rectified using a combination of Image Enhancement and modification of the Image Sensitivity parameter. The Image Enhancement option chosen was Binary. A binary image is a digital image that has only two possible values for each pixel [40]. When the image is converted to the binary, the edges of the collar of the pin are more discernible than the edges of the slots in the recess. Figure 7-9 shows the edge detection region in Binary mode.

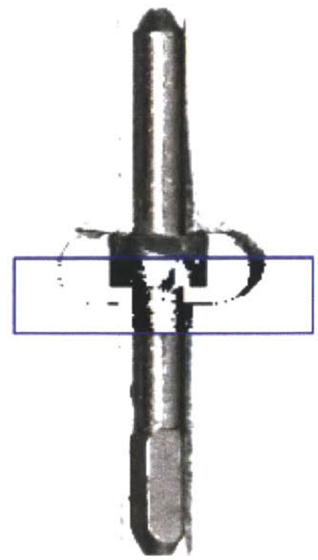


Figure 7-9: The collar of the pin has a darker edge than the slot of the recess on converting it to binary

Edge sensitivity refers to the level of intensity that is detected as an edge, where 100% represents the maximum edge intensity in the region. By specifying the edge sensitivity in relation to the maximum edge intensity in the region edge detection is very stable and robust against fluctuations in illumination [18]. The default edge sensitivity is 30%. This value was raised to 60% to avoid wrong and weak edges being detected by the system. Figure 7-10 shows the right edge detected after switching to Binary mode and increasing Edge Sensitivity.

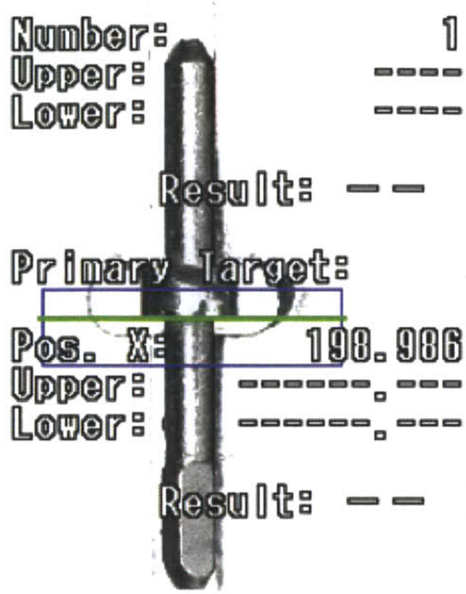


Figure 7-10: The vision system detected the right edge on converting the inspection region to binary and increasing the image sensitivity

7.2 Modified Vision Application

The application was modified to eliminate the reliability issues brought forth by the Pattern Match tool. In the modified program, Pattern Match is no more used. Instead an additional dimension was measured to identify the orientation. The 4 dimensions measured are:

1. Total length of the pin

2. Length from the observed top to the observed lower edge of the collar

3. Length from the observed bottom to the observed lower edge of the collar

4. Diameter of the pin

'Observed' refers to the edge that the vision system detects. The 'observed' top is the actual top edge of the pin if it is in right orientation and the bottom edge of the pin if it is in the wrong orientation. The modified program is as shown:

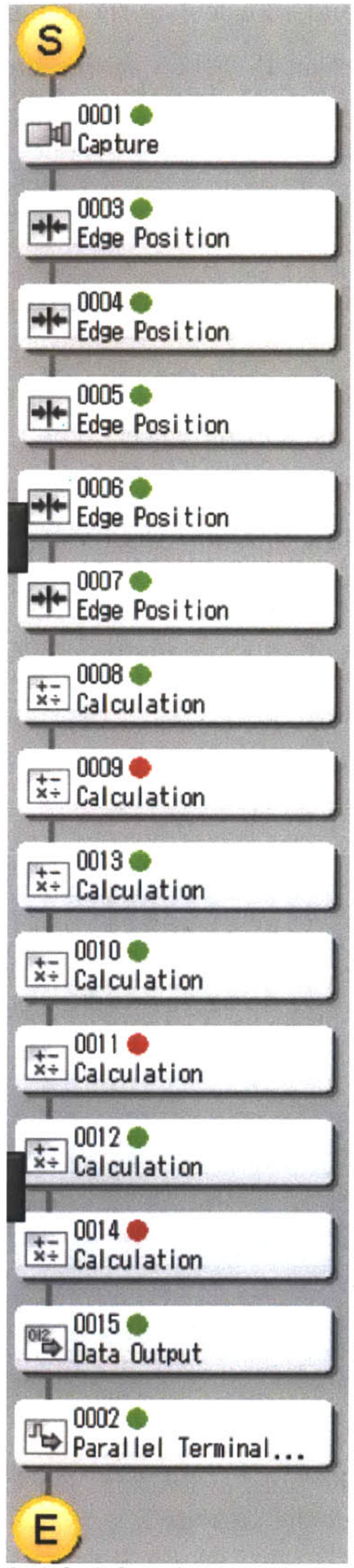


Figure 7-11: Modified flowchart without Pattern Match

Calculation steps 8, 9, 10 and 13 calculate the 4 dimensions that are of interest. Calculations 11, 12 and 13 contain IF-THEN scripts similar to the one described in Chapter 6, which helps us determine if it is the right pin and if it need re-orientation or not.

7.2.1 Results of the Modified Program

The machine vision application was tested by loading pins of the different length, but of the same diameter on the sorting wheel. The recess in sorting wheel could accommodate only pins of 0.040" diameter and hence pins of other diameters were not tested. Pins were tested in a specific order: right pin in the right orientation, right pin in the wrong orientation and wrong pin. This cycle was repeated for a total of 102 pins. Figures 7-12 and 7-13 show the total length and the length from the observed top edge to the observed lower edge of the collar.

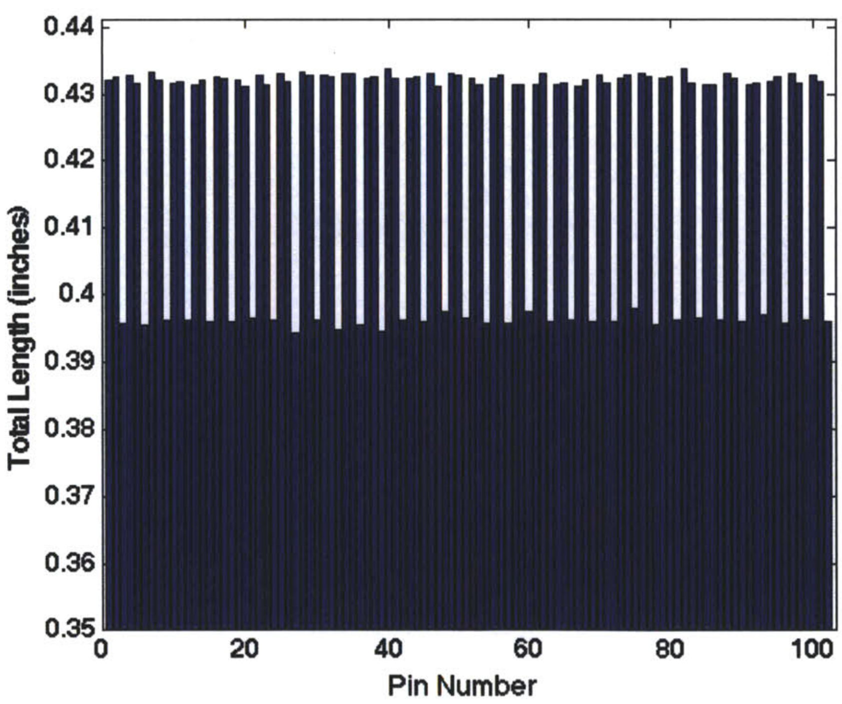


Figure 7-12: Total length of the pins; every third pin is of the wrong type and the vision system identifies it for all the pins used

The right pin is of length 0.435 inches the wrong pin of 0.400 inches. Ideally, there should be a dip in every third bar in the plot and other 2 bars should be of the same length. Figure 7-12 shows a similar pattern without there being any erroneous measurements.

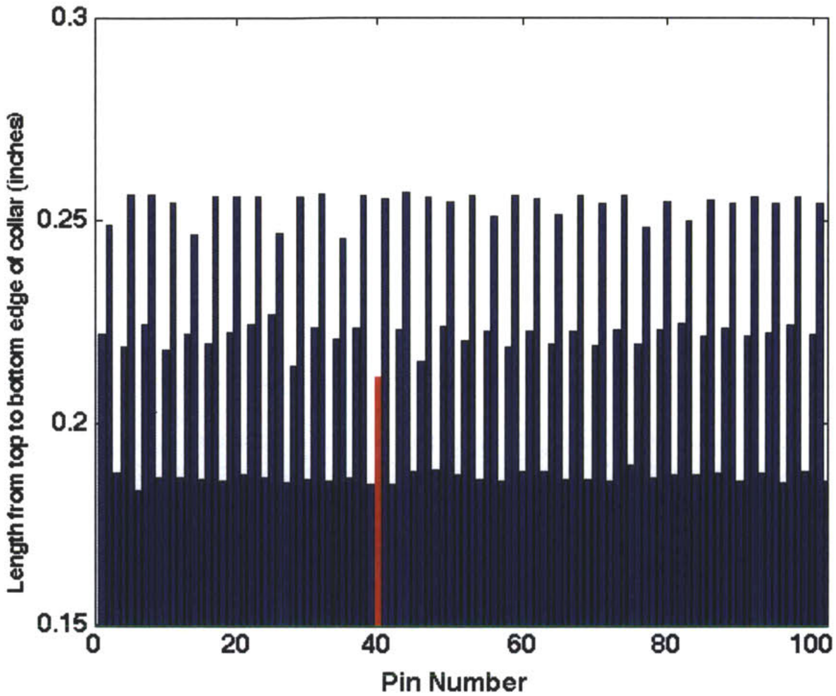


Figure 7-13: Length of the pin from the observed top of the pin to the observed lower edge of the collar. The red bar indicates a wrong measurement. This pin was of the right type in the right orientation. All oppositely oriented and wrong pin types were identified successfully

As far as the length measurement from the top edge of the pin to the lower edge of the collar is concerned, the system failed to identify one of the right pins in the right orientation. None of the wrong pins and the ones that needed re-orientation went undetected.

7.2.2 Limitations of the Modified Program

The modified program performs well for the most widely used pin type at SynQor. By changing the value of the dimensions, it can also be extended to most other pins. But SynQor does have a few pin types that have symmetrical lengths about the collar. Detecting the orientation for the symmetric pins using dimensions only is not an effective method. An alternative program, or the initial program with a more reliable pattern match needs to be used.

7.2.3 Processing Time of the Vision Application

The vision system takes about 92 ms to process one pin. This includes the time between capturing the image and sending the output to the PLC. The processing time is just about 20% of the maximum allowable time of 500 ms.

7.3 Pin Sorting Program

Delay time plays an important role in pneumatic systems as it takes some time for the pressure to build up within the circuit, as opposed to electrical circuits where electron motion is instantaneous. On testing the system, it was found that the re-orientation mechanism was the slowest of all process. Since these are parallel processes and the indexing wheel does not rotate without tasks at all stations being complete, setting the delay time for the bottleneck process is adequate. For the vacuum generators, switching delay between vacuum and compressed air was set to 100 ms. The delay time to transfer a pin from the indexing wheel to the rotary actuator was set to 300 ms. The same delay was set to transfer the pin back on to the wheel.

7.4 Pin Insertion Program

The following delay times were set to optimize the cycle time of the system. In case there was no pin in the insertion tube, the system waits for 500 ms until the pin loading cylinder extends again. A delay time of 100 ms was set for the insertion arm to start swinging once the pin escapements have opened. The pin escapements were given delay times of 100 and 200 ms for their opening and closing respectively. These delay times resulted in a cycle time of 840 ms, without considering the dwell time of 250 ms after the arm has swung.

Chapter 8

Conclusions and Future Work

8.1 Conclusions

Demand for SynQor's products has grown rapidly over the last few years and management has realized that an efficient and reliable pin insertion machine was essential to keep up with the increasing demand. The project team was successful in developing a bench-top prototype of the pin insertion machine. The system was decoupled into a pin sorting machine [2] and a pin insertion machine [3].

The pin sorting machine comprised of taking individual pins from bulk and loading the right ones into a magazine. There were some mechanical issues in the sorting mechanism that prevented us from testing the complete system [2]. Hence, the PLC program that drives the control system was tested by manually loading individual pins and it performed satisfactorily as far as sending commands for re-orienting, magazine loading and rejecting wrong pin types is concerned.

The initial application developed for the vision system was not reliable as far as detecting the orientation of the pins is concerned. The application was modified by doing away with the Pattern Match tool. Instead, the results were calculated using dimensions only. This application has an efficiency of 99% and this is significantly higher than the 30-40% efficiency that the CheckBox line scan camera on the PMJ machine can deliver. It must be noted that the system was always successful in identifying pins of wrong dimensions and opposite orientation.

The 1% loss in efficiency were the cases in which the pins of the right dimension and right orientation were rejected. This loss is not as critical to SynQor as it would be in the case of a wrong pin entering the insertion head. The application developed has a process time of 92 ms, which is only about 20% of the process time required to meet the required cycle time. The images were clear and crisp and the edges were clearly discernible. The illumination unit provided adequate intensity to produce good quality images that were sufficient to measure the dimensions and a back lighting was not found to be essential in this case.

Two different PLC programs were developed for the pin insertion machine. The first comprised of a parallel mechanism, where the time a pin is delivered to one of the insertion heads while the other is inserting a pin. The second was a serial process where the pin is delivered to the insertion head only after a pin has been inserted. Cycle time calculations were done using the second program. It returned a cycle time of 850 ms/pin, which compared well with the required cycle time of 1.25 sec/pin.

8.2 Future Work

There is additional work to be done to convert the present bench-top prototype machine into a production ready machine that can be part of the assembly line at SynQor. Some of the components on the PMJ machine can be combined with the developed system to build an efficient and reliable pin insertion machine that meets cycle time requirements.

Change the shape of the recess for the pin

The shape of the recess needs to be changed for better edge detection. The recess can be made as a vee-groove. The pin will rest in the vee-groove along its length and there is little chance of it deviating from its vertical position. Pattern Match can be used if the problem of deviation from the vertical can be done away with.

Contrasting colors for the pin and the sorting wheel

If the pin and the wheel have contrasting colors, detecting the edge of the pin will be a lot easier. The wheel can be anodized so prevent wearing away of the paint while running the machine.

Install a neutral density filter on the camera lens

It is suggested to attach a neutral density (ND) filter on the lens of the camera The ND filter reduces the intensity of all wavelengths of light equally. Presently, the brightness of the front lighting unit is set to just 4% of the maximum intensity as anything beyond this reduces the sharpness of the image. By using a neutral density filter, the intensity of the front lighting unit can be set to 100%. The optical density of the ND filter has to be high enough to allow optimum imaging conditions. A higher optical density means lower the amount of light entering the image sensor. If the brightness is set to 100%, ambient light will no longer have an effect on the image quality as its intensity is much lower than the maximum brightness of the front lighting unit.

Closed Loop Monitoring of the Stepper Position using the Vision System

The stepper on the hollow rotary indexer can lose its position over a period of time. Although it has a built-in encoder to monitor its position, a closed loop system can be built using the vision system. A change in the location of the pins in the image captured by the camera would mean that the stepper has lost its positioning accuracy. If the camera detects such deviation, the PLC can be programmed to move additional steps clockwise/counter clockwise to regain its accuracy.

Flexible mount for the camera

In the present prototype, the camera and the illumination unit are in a fixed position. The ideal position of the camera and the illumination unit might vary depending on the pin type used. It is recommended that the camera mounting design be modified with provision for both coarse and fine adjustment of the position of the camera unit.

Develop a reliable application for symmetric pins

The present machine vision application is reliable for pins that have different lengths above and below the collar. To be applicable for pins that are symmetric about the collar as far as length is concerned, an additional identifier has to be used. The initial program developed, with the pattern match tool is the ideal program as far as algorithm is concerned. It can be used for all pins, including the symmetric ones, if pattern match can be made more reliable.

Switch to a more robust PLC/Robotic Controller

The CTC Motion Controller has a few limitations in terms of its programming language, Quickstep, and the number of digital I/O. The final pin insertion machine will have a robotic controller to control the linear actuators and hence, it is preferable to control it a more flexible robotic controller than the present PLC.

Establish pin tracking system

A bar code based pin tracking system has to be established to maintain a record of the lot number of the pins that are inserted into each board, thereby giving SynQor easy access to data in case there are product defects in the future. The existing SynQor Tracking System (STS) program can be modified to accommodate the additional data generated by the bar code scanner. Figure () shows a schematic of the process.

Extend the mechanism developed to other pin insertion machines

The prototype developed by the team can be used to re-design the other pin insertion machines like the UMG, which have been facing similar reliability issues.

Appendix A

Tables

A.1 Pattern Match Percentage of Right pins in the Right Orientation

Table A.1: Pattern Match percentage of the right pin

Pin No.	Pattern Match %	Pin No.	Pattern Match %
1	91.89	51	93.935
2	86.755	52	95.251
3	91.597	53	96.683
4	87.729	54	98.016
5	89.711	55	88.486
6	97.015	56	97.36
7	90.253	57	94.861
8	94.466	58	89.137
9	90.868	59	95.451
10	86.893	60	98.012
11	88.492	61	88.707
12	87.392	62	89.488
13	98.534	63	95.027

Continued on next page

Table A.1 – *Continued from previous page*

Pin No.	Pattern Match %	Pin No.	Pattern Match %
14	94.412	64	96.353
15	91.034	65	89.012
16	95.049	66	87.337
17	89.598	67	88.298
18	97.189	68	96.098
19	94.789	69	97.87
20	91.719	70	89.728
21	94.141	71	90.991
22	89.175	72	95.163
23	90.712	73	88.631
24	98.611	74	95.862
25	94.958	75	88.249
26	91.048	76	97.618
27	93.916	77	88.875
28	89.093	78	98.007
29	97.141	79	85.458
30	98.442	80	90.651
31	94.319	81	88.686
32	91.203	82	87.921
33	94.621	83	97.838
34	88.673	84	87.997
35	89.494	85	90.746
36	90.433	86	94.501
37	94.188	87	90.091
38	90.565	88	87.74
39	94.629	89	97.737
40	95.483	90	88.179

Continued on next page

Table A.1 – *Continued from previous page*

Pin No.	**Pattern Match %**	**Pin No.**	**Pattern Match %**
41	97.189	91	97.437
42	89.307	92	91.982
43	94.652	93	88.713
44	89.934	94	87.785
45	94.426	95	97.153
46	95.406	96	91.785
47	97.008	97	95.357
48	90.985	98	88.017
49	88.426	99	96.866
50	97.815	100	89.137

A.2 Pattern Match for Pins in the Opposite Orientation

Table A.2: Pattern match for wrongly oriented pins

Pin No.	Pattern Match %	Pin No.	Pattern Match %
1	83.589	21	73.209
2	81.177	22	78.836
3	77.087	23	72.302
4	84.41	24	86.363
5	78.619	25	74.225
6	74.225	26	82.431
7	83.24	27	74.395
8	80.533	28	77.893
9	78.473	29	70.411
10	73.148	30	85.392
11	78.3	31	81.737
12	74.055	32	68.495
13	73.116	33	71.414
14	80.901	34	86.348
15	71.414	35	73.912
16	68.425	36	77.087
17	78.395	37	80.553
18	72.861	38	78.983
19	77.881	39	74.672
20	83.673	40	83.786

A.3 Data for setting dimensional tolerance on the vision system

Table A.3: Data for dimensional tolerance on the vision system

Pin No.	Total Length	Top to collar	Diameter
1	436.892	225.865	38.952
2	436.413	223.29	38.424
3	436.886	226.457	38.736
4	438.409	228.471	41.262
5	437.535	227.365	39.933
6	435.656	223.808	41.768
7	437.307	226.055	38.449
8	435.779	222.064	42.063
9	436.309	225.426	38.588
10	436.825	225.051	41.538
11	437.439	225.256	39.36
12	437.601	226.877	39.883
13	437.178	225.459	42.913
14	435.783	222.047	42.052
15	436.773	225.679	39.032
16	436.323	225.32	43.001
17	437.192	226.9	39.166
18	436.836	225.001	41.889
19	437.254	225.958	43.297
20	437.365	227.728	39.388
21	437.449	227.739	43.41
22	437.216	226.012	39.162
23	435.502	223.918	39.99
24	435.686	221.421	42.362

Continued on next page

Table A.3 – *Continued from previous page*

Pin No.	Total Length	Top to collar	Diameter
25	437.285	226.199	42.655
26	437.508	227.775	39.644
27	437.343	225.846	43.531
28	437.205	226.021	39.172
29	436.014	224.129	42.109
30	436.799	225.208	42.458
31	435.458	222.393	43.35
32	436.204	225.315	38.723
33	437.506	227.283	43.698
34	435.754	224.846	38.995
35	436.798	225.796	38.009
36	376.155	225.315	38.739
37	437.701	226.801	43.46
38	437.336	225.518	38.975
39	437.718	226.057	43.292
40	436.475	224.126	42.452
41	436.887	226.51	42.199
42	436.134	223.444	38.179
43	436.898	224.415	42.186
44	437.092	225.337	40.678
45	437.353	226.007	43.089
46	436.473	224.088	42.46
47	436.113	224.672	42.285
48	437.367	226.938	39.386
49	436.944	227.627	39.299
50	436.293	224.07	42.49
51	436.984	225.313	43.632

Continued on next page

Table A.3 – *Continued from previous page*

Pin No.	Total Length	Top to collar	Diameter
52	437.137	226.648	42.849
53	436.388	223.933	41.724
54	437.421	225.846	42.957
55	436.923	227.583	40.032
56	436.243	224.607	41.67
57	436.942	225.268	43.042
58	437.013	226.722	39.394
59	436.284	224.061	44.245
60	437.673	223.932	42.821
61	436.641	225.67	39.821
62	436.316	224.539	46.105
63	437.03	226.657	42.832
64	437.098	226.61	44.322
65	436.321	225.144	40.845
66	437.221	224.892	57.051
67	436.067	224.253	39.397
68	437.065	226.775	45.253
69	437.307	225.036	42.778
70	436.647	225.842	39.49
71	436.789	226.62	41.227
72	436.417	225.033	46.591
73	438.165	226.301	39.375
74	436.634	223.948	42.885
75	436.699	225.707	38.628
76	436.96	226.861	41.951
77	436.414	224.883	40.118
78	436.13	222.6	43.122

Continued on next page

Table A.3 – *Continued from previous page*

Pin No.	Total Length	Top to collar	Diameter
79	436.754	226.262	42.327
80	436.293	225.859	39.581
81	438.052	226.831	39.4
82	435.951	226.128	38.002
83	437.298	225.584	43.153
84	436.601	226.197	38.646
85	437.938	228.138	41.563
86	437.637	229.165	46.861
87	437.279	226.764	40.18
88	435.679	223.898	38.14
89	436.685	224.928	42.82
90	436.603	226.383	40.877
91	437.487	228.544	42.842
92	438.469	227.796	45.071
93	437.16	225.584	39.597
94	435.721	223.563	38.097
95	436.147	222.822	43.736
96	436.406	226.71	39.11
97	437.609	222.192	46.92
98	436.011	224.836	39.553
99	437.087	225.86	42.413
100	437.013	226.722	39.394

A.4 Data from the modified vision application

Table A.4: Data from the modified vision application

Pin No.	Total Length	Top to collar
1	431.995	222.025
2	432.441	248.554
3	395.702	187.544
4	432.852	218.881
5	431.577	256.21
6	395.473	183.149
7	433.197	224.29
8	432.121	256.292
9	396.118	186.36
10	431.531	218.061
11	431.825	254.303
12	396.246	186.275
13	431.224	221.825
14	432.092	246.198
15	395.977	186.224
16	432.507	219.342
17	432.228	255.739
18	396.085	185.85
19	432.041	222.372
20	431.201	255.792
21	396.546	187.239
22	432.75	224.176
23	431.35	255.914
24	396.263	186.272
25	433.082	226.476
26	431.753	246.688
27	394.41	185.383

Continued on next page

Table A.4 – *Continued from previous page*

Pin No.	Total Length	Top to collar
28	433.354	214.018
29	432.807	255.869
30	396.252	186.13
31	432.854	223.605
32	432.426	256.565
33	394.859	185.513
34	432.975	220.864
35	432.967	245.466
36	395.457	186.48
37	432.313	223.598
38	432.569	256.357
39	394.426	184.825
40	433.618	211.286
41	432.255	255.536
42	396.161	184.717
43	432.281	223.052
44	432.49	256.943
45	395.865	188.19
46	433.061	215.155
47	431.174	255.602
48	397.297	188.474
49	432.968	223.89
50	432.808	254.412
51	396.348	187.426
52	432.266	220.439
53	431.35	256.002
54	395.641	185.863

Continued on next page

Table A.4 – *Continued from previous page*

Pin No.	**Total Length**	**Top to collar**
55	432.362	222.859
56	432.844	251.204
57	395.735	185.656
58	431.378	218.898
59	431.351	256.082
60	397.379	187.873
61	431.274	222.675
62	433.05	255.341
63	395.991	187.996
64	431.292	219.651
65	431.471	251.398
66	396.126	186.142
67	431.043	222.534
68	432.083	256.234
69	395.976	186.026
70	432.82	219.187
71	431.623	254.303
72	396.074	185.461
73	432.346	223.067
74	432.839	256.331
75	397.909	189.554
76	432.936	219.475
77	432.441	248.446
78	395.409	186.608
79	432.314	223.087
80	432.506	254.585
81	396.317	187.079

Continued on next page

Table A.4 – *Continued from previous page*

Pin No.	Total Length	Top to collar
82	433.744	224.622
83	431.514	249.871
84	396.521	187.039
85	431.359	221.596
86	431.328	255.018
87	396.325	187.427
88	432.938	223.474
89	432.368	254.293
90	396.086	185.549
91	431.361	221.685
92	431.463	255.869
93	396.983	187.614
94	431.866	222.165
95	432.483	254.047
96	395.65	185.112
97	432.985	224.072
98	431.512	255.862
99	396.292	187.962
100	432.776	221.813
101	431.778	254.288
102	395.897	185.76

Appendix B

PLC Programs

B.1 Pin Sorting Program

[1] Begin

;;; Start the program

<TURN OFF ALL DIGITAL OUTPUTS>

---

store 0 to Solenoid_at_LoadPin_Station_Reg501

store 1 to Solenoid_at_Reject_Station_Reg506

store 2 to Solenoid_at_LoadMagazine_Station_Reg505

store 3 to Solenoid_at_Reorient_Station_Reg504

store 4 to Solenoid_at_Camera_Station_Reg503

store 5 to Solenoid_at_Dummy_Station_Reg502

goto Next

[2] Air_Supply_On

;;; Turn on the air supply

Air_OP1_On

---

goto Next

[3] Profile_Motor

;;; Initialize the motor

<NO CHANGE IN DIGITAL OUTPUTS>

---

profile sorting_stepper maxspeed=30000 accel=15000

goto Next

[4] Index_Wheel

;;; Turn the stepper counter clockwise 60 degrees

<NO CHANGE IN DIGITAL OUTPUTS>

---

turn sorting_stepper ccw 30000 steps

monitor sorting_stepper:stopped goto Next

[5] Update_Counters

;;; These counters store the solenoid number in front of each station

---

<NO CHANGE IN DIGITAL OUTPUTS>

---

store Solenoid_at_LoadPin_Station_Reg501 + 1

to Solenoid_at_LoadPin_Station_Reg501

if Solenoid_at_LoadPin_Station_Reg501 > 6

goto Reset_LoadPin_Station_Counter

store Solenoid_at_Reject_Station_Reg506 + 1

to Solenoid_at_Reject_Station_Reg506

if Solenoid_at_Reject_Station_Reg506 > 6 goto Reset_Reject_Station_Counter

store Solenoid_at_LoadMagazine_Station_Reg505 + 1

to Solenoid_at_LoadMagazine_Station_Reg505

if Solenoid_at_LoadMagazine_Station_Reg505 > 6

goto Reset_LoadMagazine_Station_Counter

store Solenoid_at_Reorient_Station_Reg504 + 1

to Solenoid_at_Reorient_Station_Reg504

if Solenoid_at_Reorient_Station_Reg504 > 6

goto Reset_Reorient_Station_Counter

store Solenoid_at_Camera_Station_Reg503 + 1

to Solenoid_at_Camera_Station_Reg503

if Solenoid_at_Camera_Station_Reg503 > 6

goto Reset_Camera_Station_Counter

store Solenoid_at_Dummy_Station_Reg502 + 1

to Solenoid_at_Dummy_Station_Reg502

if Solenoid_at_Dummy_Station_Reg502 > 6

goto Reset_Dummy_Station_Counter

goto Branch_Out

[6] Reset_LoadPin_Station_Counter

<NO CHANGE IN DIGITAL OUTPUTS>

---

store 1 to Solenoid_at_LoadPin_Station_Reg501

store 2 to Solenoid_at_Reject_Station_Reg506

store 3 to Solenoid_at_LoadMagazine_Station_Reg505

store 4 to Solenoid_at_Reorient_Station_Reg504

store 5 to Solenoid_at_Camera_Station_Reg503

store 6 to Solenoid_at_Dummy_Station_Reg502

goto Branch_Out

[7] Reset_Dummy_Station_Counter

<NO CHANGE IN DIGITAL OUTPUTS>

---

store 1 to Solenoid_at_Dummy_Station_Reg502

store 2 to Solenoid_at_LoadPin_Station_Reg501

store 3 to Solenoid_at_Reject_Station_Reg506

store 4 to Solenoid_at_LoadMagazine_Station_Reg505

store 5 to Solenoid_at_Reorient_Station_Reg504

store 6 to Solenoid_at_Camera_Station_Reg503

goto Branch_Out

[8] Reset_Camera_Station_Counter

<NO CHANGE IN DIGITAL OUTPUTS>

---

store 1 to Solenoid_at_Camera_Station_Reg503

store 2 to Solenoid_at_Dummy_Station_Reg502

store 3 to Solenoid_at_LoadPin_Station_Reg501

store 4 to Solenoid_at_Reject_Station_Reg506

store 5 to Solenoid_at_LoadMagazine_Station_Reg505

store 6 to Solenoid_at_Reorient_Station_Reg504

goto Branch_Out

[9] Reset_Reorient_Station_Counter

<NO CHANGE IN DIGITAL OUTPUTS>

---

store 1 to Solenoid_at_Reorient_Station_Reg504

store 2 to Solenoid_at_Camera_Station_Reg503
store 3 to Solenoid_at_Dummy_Station_Reg502
store 4 to Solenoid_at_LoadPin_Station_Reg501
store 5 to Solenoid_at_Reject_Station_Reg506
store 6 to Solenoid_at_LoadMagazine_Station_Reg505
goto Branch_Out

[10] Reset_LoadMagazine_Station_Counter

<NO CHANGE IN DIGITAL OUTPUTS>

---

store 1 to Solenoid_at_LoadMagazine_Station_Reg505
store 2 to Solenoid_at_Reorient_Station_Reg504
store 3 to Solenoid_at_Camera_Station_Reg503
store 4 to Solenoid_at_Dummy_Station_Reg502
store 5 to Solenoid_at_LoadPin_Station_Reg501
store 6 to Solenoid_at_Reject_Station_Reg506
goto Branch_Out

[11] Reset_Reject_Station_Counter

<NO CHANGE IN DIGITAL OUTPUTS>

---

store 1 to Solenoid_at_Reject_Station_Reg506
store 2 to Solenoid_at_LoadMagazine_Station_Reg505
store 3 to Solenoid_at_Reorient_Station_Reg504
store 4 to Solenoid_at_Camera_Station_Reg503
store 5 to Solenoid_at_Dummy_Station_Reg502
store 6 to Solenoid_at_LoadPin_Station_Reg501
goto Branch_Out

[12] Branch_Out

;;; Start parallel steps at each station

<NO CHANGE IN DIGITAL OUTPUTS>

---

do (Load_Pin_Station Dummy_Station Camera_Station Reorient_Station Load_Magazine_Station Reject_Station) goto Index_Wheel

[13] Load_Pin_Station

;;; Loading pin onto the wheel from the bowl feeder

<NO CHANGE IN DIGITAL OUTPUTS>

---

if Solenoid_at_LoadPin_Station_Reg501=1 goto Turn_Solenoid1_LoadPin_Air_Off

if Solenoid_at_LoadPin_Station_Reg501=2 goto Turn_Solenoid2_LoadPin_Air_Off

if Solenoid_at_LoadPin_Station_Reg501=3 goto Turn_Solenoid3_LoadPin_Air_Off

if Solenoid_at_LoadPin_Station_Reg501=4 goto Turn_Solenoid4_LoadPin_Air_Off

if Solenoid_at_LoadPin_Station_Reg501=5 goto Turn_Solenoid5_LoadPin_Air_Off

if Solenoid_at_LoadPin_Station_Reg501=6 goto Turn_Solenoid6_LoadPin_Air_Off

[14] Turn_Solenoid1_LoadPin_Air_Off

;;; Turn the air blow off on the valve

Solenoid1_Air_OP3_Off

---

delay 100 ms goto Next

[15] Turn_Solenoid1_LoadPin_Vacuum_On

Solenoid1_Vacuum_OP2_On

---

delay 100 ms goto Load_Pin_Done

[16] Turn_Solenoid2_LoadPin_Air_Off

;;; Turn on vacuum on the valve

Solenoid2_Air_OP5_Off

---

delay 100 ms goto Next

[17] Turn_Solenoid2_LoadPin_Vacuum_On

Solenoid2_Vacuum_OP4_On

---

delay 100 ms goto Load_Pin_Done

[18] Turn_Solenoid3_LoadPin_Air_Off

Solenoid3_Air_OP7_Off

---

delay 100 ms goto Next

[19] Turn_Solenoid3_LoadPin_Vacuum_On

Solenoid3_Vacuum_OP6_On

---

delay 100 ms goto Load_Pin_Done

[20] Turn_Solenoid4_LoadPin_Air_Off

Solenoid4_Air_OP9_Off

Solenoid4_Vacuum_OP8_On

---

delay 100 ms goto Next

[21] Turn_Solenoid4_LoadPin_Vacuum_On

Solenoid4_Vacuum_OP8_On

---

delay 100 ms goto Load_Pin_Done

[22] Turn_Solenoid5_LoadPin_Air_Off

Solenoid5_Air_OP11_Off

Solenoid5_Vacuum_OP10_On

---

delay 100 ms goto Next

[23] Turn_Solenoid5_LoadPin_Vacuum_On

Solenoid5_Vacuum_OP10_On

---

delay 100 ms goto Load_Pin_Done

[24] Turn_Solenoid6_LoadPin_Air_Off

Solenoid6_Air_OP13_Off

---

delay 100 ms goto Next

[25] Turn_Solenoid6_LoadPin_Vacuum_On

Solenoid6_Vacuum_OP12_On

---

delay 100 ms goto Load_Pin_Done

[26] Load_Pin_Done

;;; Loading pin done

<NO CHANGE IN DIGITAL OUTPUTS>

---

done

[27] Camera_Station

;;; Trigger camera and monitor the inputs

;;; RPRO is Right Pin Right Orientation

;;; RPWO is Right Pin Wrong Orientation

;;; WP is Wrong Pin

Trigger_Camera_OP17_On

---

delay 1 sec goto Monitor_Inputs

[28] Monitor_Inputs

<NO CHANGE IN DIGITAL OUTPUTS>

---

monitor RPRO goto RightPin_RightOrientation

monitor RPWO goto RightPin_WrongOrientation monitor WP goto WrongPin

[29] RightPin_RightOrientation

;;; If the pin is RPRO store 5 to the pin release station register.

;;; 5 refers to Station 5(Magazine Filling Station)

;;; The data table stores the station at which a pin has to be released

;;; Reg 126 loactes the row number and Release Station writes the release

;;; station in the first column of that row

Trigger_Camera_OP17_Off

---

store Solenoid_at_Camera_Station_Reg503 to Data_Table_Row_Pointer_Reg126

store 5 to Pin_Release_Station_Col1

delay 200 ms goto Camera_Station_Done

[30] RightPin_WrongOrientation

;;; 4 refers to the reorienting station

Trigger_Camera_OP17_Off

---

store Solenoid_at_Camera_Station_Reg503 to Data_Table_Row_Pointer_Reg126

store 4 to Pin_Release_Station_Col1

delay 200 ms goto Camera_Station_Done

[31] WrongPin

;;; 6 refers to the reject station

Trigger_Camera_OP17_Off

---

store Solenoid_at_Camera_Station_Reg503 to Data_Table_Row_Pointer_Reg126

store 6 to Pin_Release_Station_Col1
delay 200 ms goto Camera_Station_Done

[32] Camera_Station_Done

<NO CHANGE IN DIGITAL OUTPUTS>

---

done

[33] Reorient_Station
;;; This step checks for the Release station (column 1) for the valve that
;;; is in front of the reorienting station. If the release station is 4, it
;;; has to be reoriented, else the process at this station is over.

<NO CHANGE IN DIGITAL OUTPUTS>

---

store Solenoid_at_Reorient_Station_Reg504 to Data_Table_Row_Pointer_Reg126
if Pin_Release_Station_Col1=4 goto Find_Solenoid_Number_for_Reorient
goto Reorient_Done

[34] Find_Solenoid_Number_for_Reorient
;;; Find the valve number whose vacuum has to be turned off.
;;; Turn on the vacuum on the rotary actuator

Reorient_Vacuum_OP14_On

---

if Solenoid_at_Reorient_Station_Reg504=1 goto Turn_Solenoid1_Reorient_Vacuum_Off
if Solenoid_at_Reorient_Station_Reg504=2 goto Turn_Solenoid2_Reorient_Vacuum_Off
if Solenoid_at_Reorient_Station_Reg504=3 goto Turn_Solenoid3_Reorient_Vacuum_Off
if Solenoid_at_Reorient_Station_Reg504=4 goto Turn_Solenoid4_Reorient_Vacuum_Off

if Solenoid_at_Reorient_Station_Reg504=5 goto Turn_Solenoid5_Reorient_Vacuum_Off
if Solenoid_at_Reorient_Station_Reg504=6 goto Turn_Solenoid6_Reorient_Vacuum_Off

[35] Turn_Solenoid1_Reorient_Vacuum_Off

;;; Turn off vacuum on valve 1 and turn on the air blow.

;;; Go to Flip Pin step

Solenoid1_Vacuum_OP2_Off

---

delay 100 ms goto Next

[36] Turn_Solenoid1_Reorient_Air_On

Solenoid1_Air_OP3_On

---

delay 100 ms goto Flip_Pin

[37] Turn_Solenoid2_Reorient_Vacuum_Off

Solenoid2_Vacuum_OP4_Off

---

delay 100 ms goto Next

[38] Turn_Solenoid2_Reorient_Air_On

Solenoid2_Air_OP5_On

---

delay 100 ms goto Flip_Pin

[39] Turn_Solenoid3_Reorient_Vacuum_Off

Solenoid3_Vacuum_OP6_Off

---

delay 100 ms goto Next

[40] Turn_Solenoid3_Reorient_Air_On

Solenoid3_Air_OP7_On

---

delay 100 ms goto Flip_Pin

[41] Turn_Solenoid4_Reorient_Vacuum_Off

Solenoid4_Vacuum_OP8_Off

---

delay 100 ms goto Next

[42] Turn_Solenoid4_Reorient_Air_On

Solenoid4_Air_OP9_On

---

delay 100 ms goto Flip_Pin

[43] Turn_Solenoid5_Reorient_Vacuum_Off

Solenoid5_Vacuum_OP10_Off

---

delay 100 ms goto Next

[44] Turn_Solenoid5_Reorient_Air_On

Solenoid5_Air_OP11_On

---

delay 100 ms goto Flip_Pin

[45] Turn_Solenoid6_Reorient_Vacuum_Off

Solenoid6_Vacuum_OP12_Off

---

delay 100 ms goto Next

[46] Turn_Solenoid6_Reorient_Air_On

Solenoid6_Air_OP13_On

---

delay 100 ms goto Flip_Pin

[47] Flip_Pin
;;; Turn the rotary actuator 180 degrees

Flip_Pin_OP16_On

---

delay 300 ms goto Transfer_Pin_to_Wheel

[48] Transfer_Pin_to_Wheel
;;; Turn off vacuum on rotary actuator and find the vavle whose
;;; vacuum needs to be turned on

Reorient_Vacuum_OP14_Off

---

if Solenoid_at_Reorient_Station_Reg504=1 goto Turn_Solenoid1_Reor_TransfrBk_Air_Off
if Solenoid_at_Reorient_Station_Reg504=2 goto Turn_Solenoid2_Reor_TransfrBk_Air_Off
if Solenoid_at_Reorient_Station_Reg504=3 goto Turn_Solenoid3_Reor_TransfrBk_Air_Off
if Solenoid_at_Reorient_Station_Reg504=4 goto Turn_Solenoid4_Reor_TransfrBk_Air_Off
if Solenoid_at_Reorient_Station_Reg504=5 goto Turn_Solenoid5_Reor_TransfrBk_Air_Off
if Solenoid_at_Reorient_Station_Reg504=6 goto Turn_Solenoid6_Reor_TransfrBk_Air_Off

[49] Turn_Solenoid1_Reor_TransfrBk_Air_Off

;;; Turn the blow off on valve 1;turn on vacuum and turn on the blow
;;; on the rotary actuator

Solenoid1_Air_OP3_Off
Reorient_Air_OP15_On

---

store Solenoid_at_Reorient_Station_Reg504 to Data_Table_Row_Pointer_Reg126
store 5 to Pin_Release_Station_Col1
delay 100 ms goto Next

[50] Turn_Solenoid1_Reor_TransfrBk_Vacuum_On

Solenoid1_Vacuum_OP2_On

---

delay 300 ms goto Reorient_Done

[51] Turn_Solenoid2_Reor_TransfrBk_Air_Off

Solenoid2_Air_OP5_Off
Reorient_Air_OP15_On

---

store Solenoid_at_Reorient_Station_Reg504 to Data_Table_Row_Pointer_Reg126

store 5 to Pin_Release_Station_Col1

delay 100 ms goto Next

[52] Turn_Solenoid2_Reor_TransfrBk_Vacuum_On

Solenoid2_Vacuum_OP4_On

---

delay 300 ms goto Reorient_Done

[53] Turn_Solenoid3_Reor_TransfrBk_Air_Off

Solenoid3_Air_OP7_Off

Reorient_Air_OP15_On

---

store Solenoid_at_Reorient_Station_Reg504 to Data_Table_Row_Pointer_Reg126

store 5 to Pin_Release_Station_Col1

delay 100 ms goto Next

[54] Turn_Solenoid3_Reor_TransfrBk_Vacuum_On

Solenoid3_Vacuum_OP6_On

---

delay 300 ms goto Reorient_Done

[55] Turn_Solenoid4_Reor_TransfrBk_Air_Off

Solenoid4_Air_OP9_Off

Reorient_Air_OP15_On

---

store Solenoid_at_Reorient_Station_Reg504 to Data_Table_Row_Pointer_Reg126

store 5 to Pin_Release_Station_Col1
delay 100 ms goto Next

[56] Turn_Solenoid4_Reor_TransfrBk_Vacuum_On

Solenoid4_Vacuum_OP8_On

---

delay 300 ms goto Reorient_Done

[57] Turn_Solenoid5_Reor_TransfrBk_Air_Off

Solenoid5_Air_OP11_Off
Reorient_Air_OP15_On

---

store Solenoid_at_Reorient_Station_Reg504 to Data_Table_Row_Pointer_Reg126
store 5 to Pin_Release_Station_Col1
delay 100 ms goto Next

[58] Turn_Solenoid5_Reor_TransfrBk_Vacuum_On

Solenoid5_Vacuum_OP10_On

---

delay 300 ms goto Reorient_Done

[59] Turn_Solenoid6_Reor_TransfrBk_Air_Off

Solenoid6_Air_OP13_Off
Reorient_Air_OP15_On

---

store Solenoid_at_Reorient_Station_Reg504 to Data_Table_Row_Pointer_Reg126

store 5 to Pin_Release_Station_Col1

delay 100 ms goto Next

[60] Turn_Solenoid6_Reor_TransfrBk_Vacuum_On

Solenoid6_Vacuum_OP12_On

---

delay 300 ms goto Reorient_Done

[61] Reorient_Done

Reorient_Air_OP15_Off

Flip_Pin_OP16_Off

---

done

[62] Load_Magazine_Station

;;; Find if the pin in front of the magazine loading station is supposed

;;; to enter the magazine

<NO CHANGE IN DIGITAL OUTPUTS>

---

store Solenoid_at_LoadMagazine_Station_Reg505 to Data_Table_Row_Pointer_Reg126

if Pin_Release_Station_Col1=5 goto Find_Solenoid_Number_for_LoadMagazine

goto Load_Magazine_Done

[63] Find_Solenoid_Number_for_LoadMagazine

;;; Find the valve number whose vacuum needs to be turned off

---

<NO CHANGE IN DIGITAL OUTPUTS>

---

if Solenoid_at_LoadMagazine_Station_Reg505=1 goto Turn_Solenoid1_LoadMag_Vacuum_Off
if Solenoid_at_LoadMagazine_Station_Reg505=2 goto Turn_Solenoid2_LoadMag_Vacuum_Off
if Solenoid_at_LoadMagazine_Station_Reg505=3 goto Turn_Solenoid3_LoadMag_Vacuum_Off
if Solenoid_at_LoadMagazine_Station_Reg505=4 goto Turn_Solenoid4_LoadMag_Vacuum_Off
if Solenoid_at_LoadMagazine_Station_Reg505=5 goto Turn_Solenoid5_LoadMag_Vacuum_Off
if Solenoid_at_LoadMagazine_Station_Reg505=6 goto Turn_Solenoid6_LoadMag_Vacuum_Off

[64] Turn_Solenoid1_LoadMag_Vacuum_Off

;;; Turn off vacuum on valve 1 and turn on the blow

Solenoid1_Vacuum_OP2_Off

Solenoid1_Air_OP3_On

---

delay 100 ms goto Next

[65] Turn_Solenoid1_LoadMag_Air_On

Solenoid1_Air_OP3_On

---

delay 100 ms goto Load_Magazine_Done

[66] Turn_Solenoid2_LoadMag_Vacuum_Off

Solenoid2_Vacuum_OP4_Off

---

delay 100 ms goto Next

[67] Turn_Solenoid2_LoadMag_Air_On

Solenoid2_Air_OP5_On ———————————————————————

delay 100 ms goto Load_Magazine_Done

[68] Turn_Solenoid3_LoadMag_Vacuum_Off

Solenoid3_Vacuum_OP6_Off

---

delay 100 ms goto Next

[69] Turn_Solenoid3_LoadMag_Air_On

Solenoid3_Air_OP7_On

---

delay 100 ms goto Load_Magazine_Done

[70] Turn_Solenoid4_LoadMag_Vacuum_Off

Solenoid4_Vacuum_OP8_Off

---

delay 100 ms goto Next

[71] Turn_Solenoid4_LoadMag_Air_On

Solenoid4_Air_OP9_On

---

delay 100 ms goto Load_Magazine_Done

[72] Turn_Solenoid5_LoadMag_Vacuum_Off

Solenoid5_Vacuum_OP10_Off

delay 100 ms goto Next

[73] Turn_Solenoid5_LoadMag_Air_On

Solenoid5_Air_OP11_On

delay 100 ms goto Load_Magazine_Done

[74] Turn_Solenoid6_LoadMag_Vacuum_Off

Solenoid6_Vacuum_OP12_Off

delay 100 ms goto Next

[75] Turn_Solenoid6_LoadMag_Air_On

Solenoid6_Air_OP13_On

delay 100 ms goto Load_Magazine_Done

[76] Load_Magazine_Done

<NO CHANGE IN DIGITAL OUTPUTS>

done

[77] Reject_Station

;;; Find out if the pin has to be rejected

<NO CHANGE IN DIGITAL OUTPUTS>

---

store Solenoid_at_Reject_Station_Reg506 to Data_Table_Row_Pointer_Reg126
if Pin_Release_Station_Col1=6 goto Find_Solenoid_Number_for_Reject
goto Reject_Done

[78] Find_Solenoid_Number_for_Reject

<NO CHANGE IN DIGITAL OUTPUTS>

---

if Solenoid_at_Reject_Station_Reg506=1 goto Turn_Solenoid1_Reject_Vacuum_Off
if Solenoid_at_Reject_Station_Reg506=2 goto Turn_Solenoid2_Reject_Vacuum_Off
if Solenoid_at_Reject_Station_Reg506=3 goto Turn_Solenoid3_Reject_Vacuum_Off
if Solenoid_at_Reject_Station_Reg506=4 goto Turn_Solenoid4_Reject_Vacuum_Off
if Solenoid_at_Reject_Station_Reg506=5 goto Turn_Solenoid5_Reject_Vacuum_Off
if Solenoid_at_Reject_Station_Reg506=6 goto Turn_Solenoid6_Reject_Vacuum_Off

[79] Turn_Solenoid1_Reject_Vacuum_Off

Solenoid1_Vacuum_OP2_Off

---

delay 100 ms goto Next

[80] Turn_Solenoid1_Reject_Air_On

Solenoid1_Air_OP3_On

---

delay 100 ms goto Reject_Done

[81] Turn_Solenoid2_Reject_Vacuum_Off

Solenoid2_Vacuum_OP4_Off

delay 100 ms goto Next

[82] Turn_Solenoid2_Reject_Air_On

Solenoid2_Air_OP5_On

delay 100 ms goto Reject_Done

[83] Turn_Solenoid3_Reject_Vacuum_Off

Solenoid3_Vacuum_OP6_Off

delay 100 ms goto Next

[84] Turn_Solenoid3_Reject_Air_On

Solenoid3_Air_OP7_On

delay 100 ms goto Reject_Done

[85] Turn_Solenoid4_Reject_Vacuum_Off

Solenoid4_Vacuum_OP8_Off

delay 100 ms goto Next

[86] Turn_Solenoid4_Reject_Air_On

Solenoid5_Air_OP11_On

delay 100 ms goto Reject_Done

[87] Turn_Solenoid5_Reject_Vacuum_Off

Solenoid5_Vacuum_OP10_Off

delay 100 ms goto Next

[88] Turn_Solenoid5_Reject_Air_On

Solenoid5_Air_OP11_On

delay 100 ms goto Reject_Done

[89] Turn_Solenoid6_Reject_Vacuum_Off

Solenoid6_Vacuum_OP12_Off

delay 100 ms goto Next

[90] Turn_Solenoid6_Reject_Air_On

Solenoid6_Air_OP13_On

delay 100 ms goto Reject_Done

[91] Reject_Done

<NO CHANGE IN DIGITAL OUTPUTS>

---

done

[92] Dummy_Station

;;; No function for this station (Station 2)

<NO CHANGE IN DIGITAL OUTPUTS>

---

done

B.2 Pin Insertion Program

[1] Initialize

<TURN OFF ALL DIGITAL OUTPUTS>

---

store 1 to Odd_Even_Step_Reg501

store 10 to Cylinder_Extend_Delay_Reg503

store 5 to Cylinder_Retract_Delay_Reg504

store 2 to Vacuum_On_Delay_Reg505

store 50 to No_Pin_Detected_Delay_Reg506

store 10 to Open_Pin_Escapement_Delay_Reg507

store 0 to Delay_before_Cylinder_Extension_Reg508

store 10 to Delay_before_Arm_Swing_Reg509

store 10 to Delay_for_Arm_Settle_Reg510

store 20 to Delay_for_Pin_Escapement_Closing_Reg511

store 25 to Pin_Drop_Delay_Reg512

goto Next

[2] Pin_Blast_On

Solenoid_OP7_On

---

goto Next

[3] Extend_Cylinder

Solenoid_OP2_On

---

delay Cylinder_Extend_Delay_Reg503 sec/100 goto Next

[4] Retract_Cylinder

Solenoid_OP2_Off

---

delay Cylinder_Retract_Delay_Reg504 sec/100 goto Next

[5] Choose_Vacuum_to_turn_on

<NO CHANGE IN DIGITAL OUTPUTS>

---

if Odd_Even_Step_Reg501=1 goto Vacuum_Odd_On
goto Vacuum_Even_On

[6] Vacuum_Odd_On

Solenoid_OP6_On

---

delay Vacuum_On_Delay_Reg505 sec/100 goto Monitor_Vacuum_Odd

[7] Vacuum_Even_On

Solenoid_OP8_On

---

delay Vacuum_On_Delay_Reg505 sec/100 goto Monitor_Vacuum_Even

[8] Monitor_Vacuum_Odd

<NO CHANGE IN DIGITAL OUTPUTS>

---

monitor Pin_in_insertion_arm_A_IP17 goto Pin_detected

delay No_Pin_Detected_Delay_Reg506 sec/100 goto No_pin_detected

[9] Monitor_Vacuum_Even

<NO CHANGE IN DIGITAL OUTPUTS>

---

monitor Pin_in_insertion_arm_B_IP18 goto Pin_detected

delay No_Pin_Detected_Delay_Reg506 sec/100 goto No_pin_detected

[10] Pin_detected

<NO CHANGE IN DIGITAL OUTPUTS>

---

delay Open_Pin_Escapement_Delay_Reg507 sec/100 goto Open_Pin_Escapement

[11] No_pin_detected

<NO CHANGE IN DIGITAL OUTPUTS>

---

delay Delay_before_Cylinder_Extension_Reg508 sec/100 goto Extend_Cylinder

[12] Open_Pin_Escapement

Solenoid_OP1_On

Solenoid_OP3_On

---

delay Delay_before_Arm_Swing_Reg509 sec/100 goto Swing_Arm

[13] Swing_Arm

<NO CHANGE IN DIGITAL OUTPUTS>

---

if Odd_Even_Step_Reg501=1 goto Swing_Arm_Odd
goto Swing_Arm_Even

[14] Swing_Arm_Odd

Solenoid_OP5_On

---

monitor Arm_Swing_Complete_IP9 goto Change_to_Even

[15] Swing_Arm_Even

Solenoid_OP5_Off

---

monitor Arm_Swing_Complete_IP10 goto Change_to_Odd

[16] Change_to_Even

<NO CHANGE IN DIGITAL OUTPUTS>

---

store 2 to Odd_Even_Step_Reg501
delay Delay_for_Arm_Settle_Reg510 sec/100 goto Close_Pin_Escapement

[17] Change_to_Odd

<NO CHANGE IN DIGITAL OUTPUTS>

---

store 1 to Odd_Even_Step_Reg501

delay Delay_for_Arm_Settle_Reg510 sec/100 goto Close_Pin_Escapement

[18] Close_Pin_Escapement

Solenoid_OP1_Off

Solenoid_OP3_Off

---

delay Delay_for_Pin_Escapement_Closing_Reg511 sec/100 goto Next

[19] Turn_off_Vacuum

<NO CHANGE IN DIGITAL OUTPUTS>

---

if Odd_Even_Step_Reg501=2 goto Vacuum_Odd_Off

goto Vacuum_Even_Off

[20] Vacuum_Odd_Off

Solenoid_OP6_Off

---

delay Pin_Drop_Delay_Reg512 sec/100 goto Arm_Swing_Done

[21] Vacuum_Even_Off

Solenoid_OP8_Off

---

delay Pin_Drop_Delay_Reg512 sec/100 goto Next

[22] Arm_Swing_Done

<NO CHANGE IN DIGITAL OUTPUTS>

---

goto Extend_Cylinder

Bibliography

[1] The Surface Mount Process, ¡http://www.labortechtronicsassembly.com/smt.html¿

[2] Chang M. S., "Design of an Automated Sorting and Orienting Machine for Electronic Pins".

[3] Cook D. J., "Design and Development of an Automated Pinning Machine for the Surface Mount Electronics Industry".

[4] "PCB Pins and Receptacles Information," GlobalSpec. [Online]. [Accessed 18 June 2012].

[5] "PCB Pins and Receptacles Information," GlobalSpec, [Online]. Available: http://www.globalspec.com/learnmore/wire_connectors_interconnects/ic_interconnect_components/pcb_pins_receptacles. [Accessed 18 June 2012].

[6] P. F. Ostwald and M. Jairo, Manufacturing Processes and Systems (9th Edition), John Wiley and Sons, 1997.

[7] "Automation," Wikipedia, [Online]. Available: http://en.wikipedia.org/wiki/Automation. [Accessed 19 June 2012].

[8] "Numerical Control," Wikipedia, [Online]. Available: http://en.wikipedia.org/wiki/Numerical_Control. [Accessed 19 June 2012].

[9] M. P. Groover, Automation, Production Systems, and Computer-Integrated Manufacturing, Upper Saddle River: Pearson Education Inc., 2008.

[10] Epson Robotics, "LS-Series SCARA Robots," [Online]. Available: http://www.robots.epson.com/products/ls-series.htm. [Accessed 23 June 2012].

[11] Adept Robotics, "Adept Viper 6-Axis Robots," [Online]. Available: http://www.adept.com/products/robots/6-axis/viper-s650/general. [Accessed 22 June 2012].

[12] "Olympus Technologies," [Online]. [Accessed 21 June 2012].

[13] C. Brecher, Robot Control and Programming, Aachen, Nordrhein Westfalen: Machine Tools Laboratory (WZL), 2010.

[14] "United Nations Economic Commision for Europe," 30 October 2001. [Online]. Available: http://www.unece.org/press/pr2001/01stat10e.html. [Accessed 23 June 2012].

[15] Hardware Secrets, "How Gigabit Ethernet Works," [Online]. Available: http://www.hardwaresecrets.com/article/How-Gigabit-Ethernet-Works/231/3. [Accessed 23 June 2012]

[16] Cognex, Inc., "In-Sight 500 Vision System," [Online]. Available: http://www.cognex.com/IS500/. [Accessed 23 June 2012]

[17] Cognex, Inc., "In-Sight Micro Vision Systems," [Online]. Available: http://www.cognex.com/in-sight-micro-vision-systems.aspx. [Accessed 23 June 2012]

[18] Keyence, Inc., "Ultra High-Speed, Flexible Image Processing System," Keyence, Inc..

[19] ControlDesign.com, "Machine-Vision Market Stays Strong," [Online]. Available: http://www.controldesign.com/articles/2006/078.html. [Accessed 23 June 2012]

[20] Cognex, Inc., "Industrial Sensors: Checker," [Online]. Available: http://www.cognex.com/industrial-sensor-checker.aspx. [Accessed 23 June 2012]

[21] National Instruments, Inc., "Building a Real-Time System with NI Hardware and Software," [Online]. Available: http://www.ni.com/white-paper/4040/en. [Accessed 23 June 2012]

[22] Vision-Guided Robotics Responds to Changes in Photovoltaic Manufacturing, [Online]. Available: http://www.visiononline.org/vision-resources-details.cfm?content_id=2247 [Accessed 23 June 2012]

[23] Cognex, Inc., "New 3D Vision - Not Just any 3D, It's Cognex 3D!," [Online]. Available: http://www.cognex.com/CognexInfo/PressReleases/PressRelease.aspx?id=8577. [Accessed 23 Jun, 2012]

[24] Malamas, E., Petrakis, E., Zervakis, M., Petit, L. and Legat, J., 2003, A survey on industrial vision systems, applications and tools, Image and Vision Computing, 21(2), pp. 171-188

[25] Golanbi, H., Asadpour, A., 2003, Design and application of industrial machine vision systems, Robotics and Computer-Integrated Manufacturing 23 pp. 630637

[26] Awcock GJ, Thomas R. Applied image processing. London: Mac Millan New Press Ltd.; 1995.

[27] Gonzalez,R.C.Thomas,M.G .Syntatic Pattern Recognition:An Introduction ,Addison Wesley,Reading,MA,1978

[28] Batchelor B., Machine Vision Handbook, Springer London, 2012.

[29] Jain, R., Kasturi, R., Schunck, B., 1995, Machine Vision, Mc-Graw Hill,

[30] A Practical Guide to Machine Vision Lighting - Part III, [Online]. Available: http://www.ni.com/white-paper/6903/en, [Accessed Jun 25, 2012]

[31] 5/2-Way Solenoid Valve for Pneumatics, [Online]. Available: http://www.burkert.com/products_data/datasheets/DS6527-Standard-EU-EN.pdf, [Accessed Aug 8, 2012]

[32] Venturi Vacuum Generators: What they are and how to design them into your system, [Online]. Available: http://www.iqvalves.com/admin/productspdf/Vacuum%20Sys%20Design%20Guide.pdf, [Accessed Aug 8, 2012]

[33] Solenoid actuated vacuum generators, [Online]. Available: http://www.coastpneumatics.com/festo/temp/vacuum/2_Vacuum_Generators.pdf, [Accessed Aug 6, 2012]

[34] Kiowa, VN-05-H-T3-PQ2-VQ2-RQ2 Festo Vacuum generator, [Online]. Available: http://www.kiowa.co.uk/products/festo_vacuum_generators_vn/EF193478 [Accessed 8 Aug, 2012]

[35] SMC Corporation of America, "Pneumatic Rotary Actuator Series MSQ," [Online]. Available: http://www.smcusa.com/productsearchresults.aspx?xmlnum=20183&part number=msqb1a. [Accessed 15 Jul 2012]

[36] Spirax Sarco, "Control Valve Actuators and Positioners," [Online]. Available: http://www.spiraxsarco.com/resources/steam-engineering-tutorials/control-hardware-el-pn-actuation/control-valve-actuators-and-positioners.asp.[Accessed 15 Jul, 2012]

[37] Oriental Motors, Linear and Rotary Actuators, [Online]. Available: http://www.orientalmotor.com/catalog/brochures/DG_Brochure.pdf [Accessed 8 Aug, 2012]

[38] Quickstep Language and Programming Guide, [Online]. Available: ¡http://www.ctc-control.com/customer/techinfo/docs/QuickstepLangProg.pdf¿ [Accessed: Jun 13, 2012]

[39] Checkbox CHB-C, Compact, [Online]. Available: http://xdki.festo.com/xdki/data/doc_ENGB/PDF/EN/CHB-C_EN.PDF [Accessed Jul 23, 2012]

[40] Binary Image, [Online]. Available: http://en.wikipedia.org/wiki/Binary??image [Accessed: Aug 8, 2012]