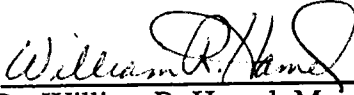
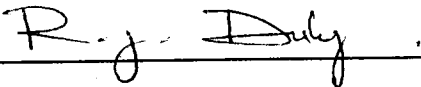


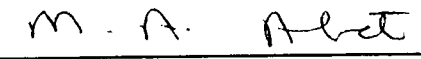
To the Graduate Council:

I am submitting herewith a thesis written by Jeffrey W. Buck entitled "Design and Development of an Automated Scanning Inspection Station". I have examined the final copy of this thesis for form and content and recommend that it be accepted in partial fulfillment of the requirements for the degree of Master of Science, with a major in Mechanical Engineering.


Dr. William R. Hamel, Major Professor

We have read this thesis
and recommend its acceptance:





Accepted for the Council:


Associate Vice Chancellor and
Dean of the Graduate School

**Design and Development of an Automated
Scanning Inspection Station**

A Thesis

Presented for the

Master of Science

Degree

The University of Tennessee, Knoxville

Jeffrey Wayne Buck

August 1996

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Abstract

General Shale Brick company has recently decided to fully automate their brick manufacturing facilities to reduce cost and improve quality control. At the Corbin, Ky., General Shale Brick manufacturing facility, only the brick dehacking process remains as an unautomated process where human workers are required to perform the physically demanding task. With General Shale's push for total automation, automation of the dehacking process is the goal. In order to accomplish this task, General Shale has teamed up with the University of Tennessee and ARTECH to develop an automated dehacking system. ARTECH has developed the automated unloading, blending and packaging system (BUPS) which performs the majority of the dehacking task. As a supplement to this, the University of Tennessee Mechanical and Aerospace and Engineering Science Department in conjunction with the Electrical Engineering Department have developed the first phase of an automatic inspection station for brick in which 2 mm cracks or larger are detected as defective. The first phase of development of the inspection station included the design and development of the overall system requirements, control system architecture and positioning mechanism. In order to accomplish this phase of the project, a feasibility study, System Design Requirements (SDR), conceptual and preliminary design and finally the detailed design have been completed. The flexible design of the inspection station was based on common and conservative design practices that are found throughout industry.

As a result of this development, the selected positioning mechanism is two parallel linear actuators powered with a single servo DC motor. The two linear actuators are mechanically linked together, and 24 volt fail-safe brakes have been implemented. Each of the linear actuators are toothed belt driven units that are completely enclosed to reduce the possibility of contamination. The controller for this system has been selected as a PC based architecture with PCI and ISA card compatibility. The mechanical design of the

inspection station has resulted in the generation of AutoCAD drawings which are given in Chapter 6. In addition to the mechanical design, the controller has been designed with a double PI (Proportional and Integral) compensator such that the system has the desired response characteristics for the inspection process.

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Nomenclature

"	Inch
1-D	One-Dimensional
2-D	Two-Dimensional
3-D	Three-Dimensional
a(t)	Acceleration
A/D	Analog to Digital
AC	Alternating Current
AML	A Manufacturing Language
b	Thickness
BUPS	Brick Unloading and Packaging System
c	Distance from neutral axis of member to outer fiber
CAD	Computer Aided Design
CPU	Central Processing Unit
D	Viscous Damping Factor ($D = \frac{T_D}{\omega}$)
D/A	Digital to Analog
d ₁	Diameter of Gear ₁
d ₂	Diameter of Gear ₂
DC	Direct Current
DFD	Data Flow Diagram
D _m	Design Margin
DoF	Degrees of Freedom
E	Modulus of Elasticity
E _{alum}	Modulus of elasticity for an aluminum member
EE	Electrical Engineering

E_g	Internally Generated Voltage
EISA	Extended Industry Standard Architecture (16 Mbyte/sec)
emf	Electromagnetic Field
E_{steel}	Modulus of elasticity for a steel member
F	Force
F_{dyn}	Dynamic Force
FEM	Finite Element Method
F_{max}	Maximum Force
F_{safety}	Factor of Safety
F_t	Force due to tension in linear actuator belt
ft-lb	Foot pounds (moment or torque)
ft/s	Feet per second (velocity)
g	Gravity
G_c	Compensator Transfer Function
GSB	General Shale Brick
h	Height
HMI	Human Machine Interface
I	Inertia
I/O	Input/Output
I_a	Armature Current
$I_{\text{actuators}}$	Inertia for the Linear Actuators
I_{alum}	Inertia for an aluminum member
I_{eff}	Effective Inertia
I_{gearbox}	Inertia for the Gearbox
IGRIP	Interactive Graphical Robot Instruction Program
I_{motor}	Inertia for the Motor

in-lb	Inch pounds (moment or torque)
in/sec ²	Inches per second squared (acceleration)
ISA	Industry Standard Architecture (8 Mbyte/sec)
I_{shaft}	Inertia for a Pulley Shaft
I_{steel}	Inertia for a steel member
J	Moment of Inertia
$j(t)$	Jerk
J_L	Load Moment of Inertia
J_m	Motor Armature Moment of Inertia
K_e	Voltage Constant of a Motor
kg	Kilogram
K_i	Integral Gain Constant
K_p	Proportional Gain Constant
K_t	Torque Constant of a Motor
Ky.	Kentucky
L	Length
L_a	Armature Inductance
lb.	Pounds
lb/in ³	Pounds per inches cubed (density)
M	Moment
m	Mass
m/s	Meters per second (velocity)
MAES	Mechanical and Aerospace Engineering and Engineering Science
MByte	Megabyte (computer data)
mm	Millimeters
M_{max}	Maximum Moment

N	Gear Ratio
OCS	Operator Control Station
OSHA	Occupational Safety and Health Agency
P	Encoder Pulse Count
PCI	Peripheral Component Interconnect (32 Mbyte/sec)
PLC	Programmable Logic Controller
psi	Pounds per square inch (pressure or stress)
R	Electrical Resistance of the Phase Windings
r	Radius of the Belt Pulley on the Linear Actuator
S	Stress
s(t)	Position
S _{crit}	Critical stress of the member
SDR	System Design Requirements
S _{max_alum}	Maximum stress for an aluminum member
S _{max_steel}	Maximum stress for a steel member
T	Torque
T _D	Damping Torque ($T_D = D\omega$)
T _F	Internal Friction Torque
T _g	Internally Generated Torque ($T_g = T_o + T_f + T_D$)
T _L	Load Torque
T _m	Motor Opposing Torque
T _o	Motor Output Torque
V	Volume
v(t)	Velocity
V _e	Electrical Voltage
W	Weight

W_{alum}	Weight for an aluminum member
$W_{\text{carry_bar}}$	Weight of the carry bar
$W_{\text{scanner_module}}$	Weight of the scanner module
W_{steel}	Weight for a steel member
W_{total}	Total weight of the member
x	Translational Position of Slider
$\ddot{x}$	Translational Acceleration of Slider
$\dot{x}$	Translational Velocity of Slider
y	Deflection
y_{crit}	Critical deflection of the member
$y_{\text{max_alum}}$	Maximum deflection for an aluminum member
$y_{\text{max_steel}}$	Maximum deflection for a steel member
$^{\circ}$	Angular Degrees
$^{\circ}\text{F}$	Degrees Fahrenheit
Greek Letters	
β	Angle of the Pulley Shaft on the Linear Actuators
η	Efficiency
θ	Angle of the Motor Shaft
$\dot{\theta}$	Angular Velocity of the Motor Shaft
$\ddot{\theta}$	Angular Acceleration of the Motor Shaft
ρ	Density
ω	Rotational Speed of Motor Shaft

Chapter One

Introduction

1.1 Background

The General Shale Brick company is a major brick manufacturer which actively pursues new technologies for improving productivity and enhancing worker effectiveness. General Shale's manufacturing plants are extensively automated, including processes that involve the integration of continuous feed material processing and batch processes associated with brick formation and firing.

One difficult manufacturing step remains essentially a manual operation. This is the step where the finished brick are removed from the kiln transport cars and prepared for packaging. The kiln cars are rail-car conveyors which transport stacks of "green" brick through the kiln to remove the moisture within the brick, causing the brick to harden. This firing stage in the kiln can have temperatures in excess of 2000° F. As the cars exit the oven, the brick are in the original stack configuration except for variations in position and orientation of the individual bricks resulting from how the brick were stacked, thermal effects of the cooling and heating stages in the firing process, and vibrations and impacts during car movement. After cooling, the brick are removed from the kiln transport cars and prepared for packaging. Presently, human workers are used at approximately nine parallel mono-rail positions to remove the brick from the kiln transport cars and prepare the brick for packaging as shown in Figure 1.1.1. The workers place from 4 to 11 bricks at a time onto the mono-rail conveyor system while inspecting the bricks for cracks, chips, edge flaws and texture/color irregularities. The defective brick are discarded into a storage area to be used in alternative ways. It is this stage of the brick manufacturing process which is



Figure 1.1.1 The Present De hacking Process at the Corbin, Ky. Plant

referred to as “de hacking” that has been resistant to automation due to the complexity of the task.

The de hacking of brick is extremely demanding physically because each worker must maintain a rate of about 2800 bricks per hour in an operation which requires torso bending and turning under high load conditions during each unloading step. As would be expected, these job positions involve high occurrences of on-the-job ailments and injuries, as well as a high employee turnover rate. For these reasons, and in the interest of job environment quality, General Shale has set out to investigate the possibility of design and implementation of an automated system to perform the “de hacking” task that has been limited to the human workers.

General Shale and the University of Tennessee have performed a feasibility study of the alternatives available for automating the dehacking task. The College of Engineering's Mechanical and Aerospace Engineering and Engineering Science (MAES), and Electrical Engineering (EE) departments performed the feasibility assessment for using robotics and computer vision technologies to automate the handling and inspection functions for the General Shale Products Company. The assessment showed that both technologies have practical merit and near-term applicability to the harsh environment and demands of operating brick plants. The feasibility assessment is discussed in greater detail in Chapter Three.

The research, design and prototyping of the on-line brick inspection system was determined to be the next phase to be pursued for General Shale in conjunction with a hard automation approach to "dehacking" brick. In order to accomplish this goal, General Shale has teamed up with ARTECH located in Arden, NC., and the University of Tennessee, Knoxville. The ARTECH company will provide the design, manufacture and installation of a Brick Unloading and Packaging System (BUPS) which will be developed using proven technologies in automation for use in a brick manufacturing facility. The new dehacking system will automatically perform the task of dehacking the brick as well as blending and packaging the brick. The BUPS will be used to transport bungs from the kiln cars to conveyor lines, break the bung down into rows of brick, then blend, regroup and package the brick for shipment. The University of Tennessee is to provide a vision based inspection system to operate as an in-line inspection station within the BUPS. The vision based inspection system will detect all cracks in the brick that have a width greater than 2 mm. A prototype inspection system will be designed, fabricated and integrated into the BUPS. The BUPS and the automatic vision based inspection station will be implemented in General Shale's Corbin, Ky., brick manufacturing facility (see Figure 1.1.2 for a

layout of the BUPS designed by ARTECH and the location of the vision based inspection station).

Currently, the General Shale Brick plant in Corbin, Ky., produces approximately 30,000 brick per hour. With the incorporation of the BUPS, four conveyor lines will be used to dehack, blend and package these brick. The bottom coarse conveyor line where the inspection station is located will carry 1/8 of the total brick distribution. It is the

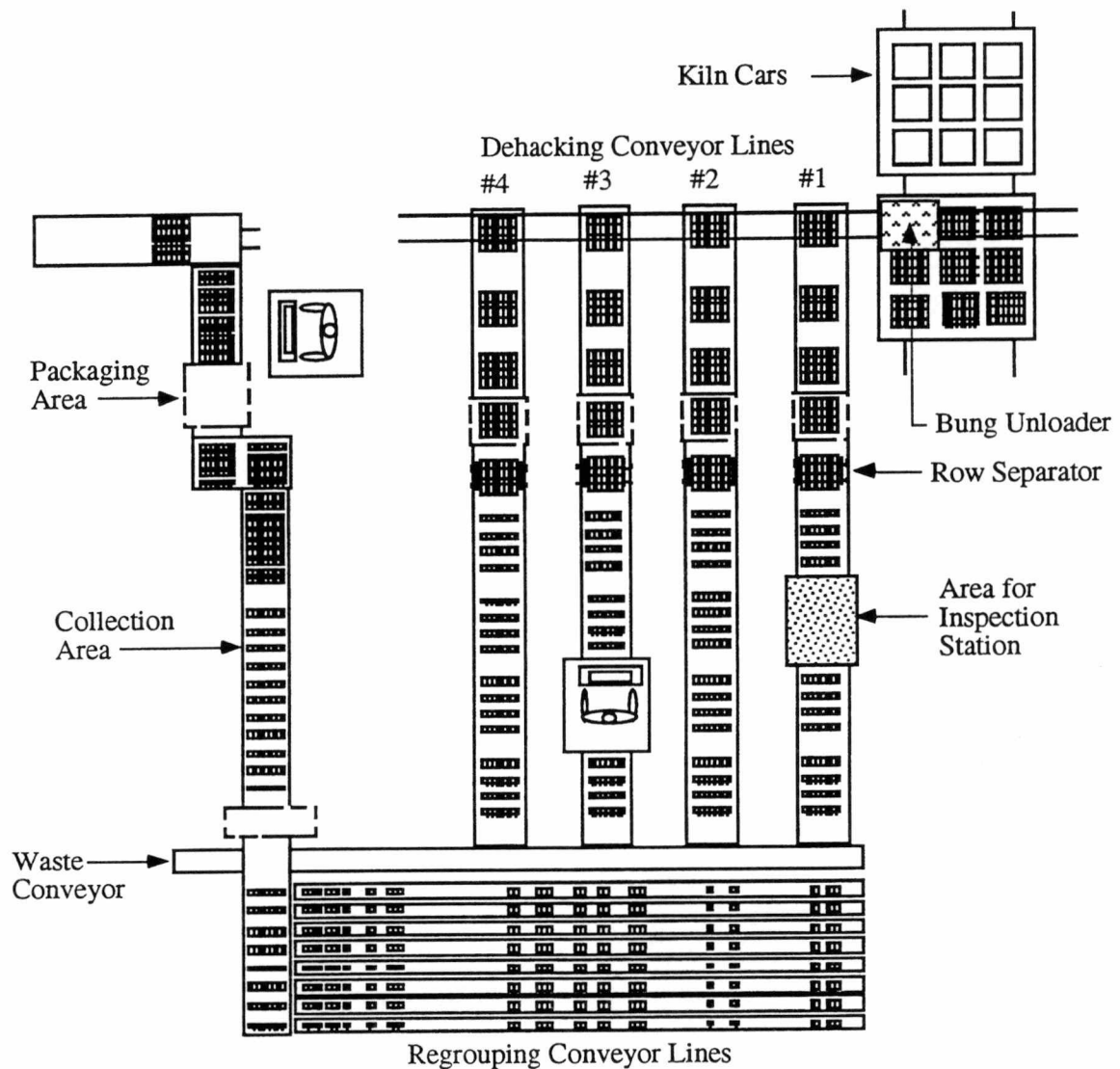


Figure 1.1.2 Layout of the Dehacking System as Designed by ARTECH

distribution of the brick among the four conveyor lines that will set the cycle times that the conveyor lines must achieve to meet the plant production rate of 30,000 brick per hour.

The inspection system will inspect all the brick on the bottom coarse conveyor in the allotted dwell time, detect all cracks of 2 mm or more and deliver the location of the “good” and “bad” brick to the BUPS. After the detection of a crack by the image analysis algorithms, that brick will be tagged as a “bad” brick and the inspection system will notify the BUPS control system of its location on the conveyor. When the BUPS is told by the inspection system that certain brick are “bad”, the tagged brick will be left on the conveyor, while the good brick are lifted and moved to another line. The bad brick which are left on the conveyor line will be transferred to a waste conveyor. The “good” brick that are transported to the next stage of conveyor lines will be regrouped for packaging with brick from all four deacking conveyor lines.

Only the bottom coarse conveyor line will contain the automatic vision based inspection station because experience has shown that approximately 98% of all defective brick are found on the bottom two coarses of the bung. The high percentage of bad brick on the bottom coarses of brick can be attributed to the thermal effects that occur between the brick in contact with the kiln cars and the fact that the bottom brick carry the weight of all other bricks in the bung [1]. In addition, only the bottom face of the brick will be inspected since almost all structural flaws and cracks occur on the bottom side of the brick. The inspection station will serve the purpose of automatically inspecting 100% of the bottom brick face for the bottom two coarses from the bung.

1.2 Problem Statement

For the design of the inspection station, the project is separated into sub-projects as it is a joint investigation for both the EE and MAES departments. The Electrical Engineering department is responsible for the selection of the scanning equipment and the

development of the computer algorithms that will be used to decide whether the brick is good or bad from the image of the brick. The MAES department is responsible for the design of the motion device that will position the scanner device for inspection, as well as integration of the inspection system with the BUPS including all control system features.

The MAES group is responsible for the design and development of the mechanical aspects of the inspection system, the integration of the inspection system controls with the BUPS overall control system, and the integration of the inspection station into the Corbin, Ky., plant. The design of the positioning system is the principal content of this thesis and will follow the design process outlined in Chapter Two. It will include detailed considerations of the mechanical support structure, evaluation of basic position mechanization alternatives, detailed design with mechanical drawings, control system design and basic integration considerations for the inspection station.

The final results of the project will be the completed design of the positioning mechanism, supporting framework and load bearing members, control system and OCS of an automatic vision based inspection station. The completion of this research project completes the first phase of the automated inspection process and will allow for phase two to begin with the EE development of the image analysis controller and algorithms. The culmination of these two phases of research will be the implementation of the automated inspection station into the Corbin, Ky., GSB plant to automatically inspect brick with limited supervisory control.

1.3 Approach and Scope

The basic approach for the design and development of the automatic vision based inspection station will follow the major areas of the design process. An overview of the design process is presented in Chapter Two, as well as major design considerations and criteria .

The basic technical approach for the inspection station uses a line scan range camera to obtain a profile of the brick array (see Figure 1.2.1 for a sketch of the brick configurations that will be inspected). The line scan range camera is used to obtain a one dimensional image which is basically a "slice" of the brick's profile, and by combining several of these 1-D slices for each brick, the general characteristics of the brick can be determined. In order to implement the design of a visual inspection station using a one dimensional scanner, a mechanical positioner is to be designed to translate the scanner over the brick. A to be developed image analysis algorithm will be used with the combined brick images for crack detection analysis. The mechanical positioner will carry the scanner (or scanners if several scanners are used) and provide the motion necessary to acquire images of the brick in accordance with the image analysis requirements as well as the overall task performance requirements.

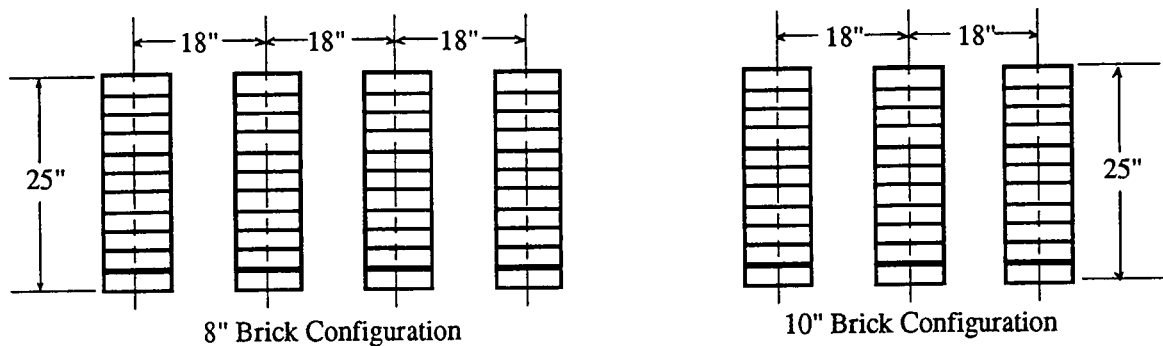


Figure 1.2.1 Brick Configurations for Inspection

The design of the mechanical positioner device will begin by defining the system requirements and finish with detailed testing and evaluation before installation into the Corbin, Ky., facility. This thesis will investigate all the steps required to insure a quality design and implement those steps in the design of the mechanical positioner and the overall inspection station.

Although the groups are independently responsible for their portion of the design, the overall performance of the inspection station is the critical factor in the design of the system. Therefore, it is necessary to understand how the image analysis is performed and what variables effect the performance of the image analysis process before the mechanical positioner can be designed. The inspection process will involve the following basic operational steps [2]:

I. Obtain an image of the brick array.

For any brick array, an original image must be obtained before any crack detection can take place. This image will be restricted to the brick array only.

II. Segment the image to isolate each brick.

Each brick array must be segmented to isolate individual bricks so that the defects can be associated with an individual brick and not just the whole array.

III. Examine the image and detect any defects.

The image of the brick array must be scanned as a whole, and defects identified by their locations. This step will be done to identify the overall location of the defects as they occur in the array.

IV. Identify the segments where the defects occur.

Once the overall locations of the defects are located, the segments, or individual brick, associated with these defect locations will be marked as defective.

V. Communicate with the PLC's (Programmable Logic Controller) indicating the location of the defective brick.

The defective brick segments have now been marked and the PLC's controlling the rejection stage grippers must be told which brick not to

accept. Communication with the PLC's will be accomplished by arranging the data sent to the PLC's in an array of ones and zeros ("high" and "low" bits respectively). Each location in the array will correspond to an individual brick. A "one" will instruct the PLC to pick up the brick, and a "zero" will inform it not to pick up the brick .

The mechanical positioner will be the mechanism by which the first step of the inspection is accomplished. The mechanical positioner device performs this task in a manner compatible with the time-spatial requirements of the image analysis algorithm and while operating safely within the target plant environment.

This thesis encompasses the design and development of the positioning mechanism and OCS (Operator Control Station) for the automatic inspection station. The design will be based on the system design requirements as outlined in Chapter Four. In particular, the mechanical positioner and inspection station controller will be developed from concept to final design for future implementation into General Shale's Corbin, Ky., brick manufacturing facility.

Chapter Two

The Engineering Design Process

2.1 Overview

This chapter presents the design methodology for which the positioning mechanism and supporting hardware for the inspection station were designed. By establishing and following a design methodology, the final design guarantees a properly engineered mechanism which addresses all aspects of the defined requirements. The design methodology for the development of the positioning mechanism was formulated from several well documented design methodologies and modified for a prototype or one-of-a-kind design.

The development of a new product is typically not by chance but by the design and determination of the product engineers in response to customer or market needs. The term, design, comes from the Latin term *designare*, which means "to designate, or mark out." Webster's definition for design is, "deliberate purposive planning, to conceive and plan out." For the development of technical and science oriented products, engineers are employed to *design* the product from conception to implementation. The engineering design process which engineers employ has been defined as "...the process of applying the various techniques and scientific principles for the purpose of defining a device, a process or a system in sufficient detail to permit its realization" [3]. The term "Engineering" can be regarded as much a method, an approach, a process, a state of mind for problem solving, as it is an activity [3].

The design and development of any product must have a predetermined path before it can ever hope to achieve its desired objective. The predetermined path for the design and development of the product is in no way applicable to all designs, but some general rules

and guidelines are typically found in any design methodology. For almost all design methodologies, the following five steps are included in some form or another [4]:

1. Recognition of Need
2. Definition of the Problem
3. Gathering Information
4. Conceptualization
5. Communication of the Design.

Although many authors have various well-documented design methodologies, no one methodology is all inclusive for all designs, but typically these five basic elements are included in any given methodology and can be expanded upon until the design methodology has up to 25 very specific steps. The design strategy is also dependent upon the type of design being conducted. Various types of designs include the following [4]:

1. One-of-a-kind design
2. Design for mass production
3. Large expensive systems
4. Design to code.

Each of these design scenarios will determine the type of methodology best suited for the particular application.

For the design and development of the mechanical positioning device for the vision based inspection station, the design is a "one-of-a-kind" type which includes some expensive and complex mechanisms. The design methodology for which this design will follow has been extrapolated from the basic requirements found in the five design steps outlined by Dieter [4], the design process found in Wilson [5] as well as the 25 years of design experience that Dr. Bill Hamel has contributed to this young engineer.

2.2 The Design Process as a Whole

By taking a closer look at the design process and beginning to extrapolate more detailed steps, the specific way the positioning mechanism should be engineered is determined. The design process for this project is shown in flow chart form in Figure 2.2.1. The arrows indicate the progression of the design as the design moves toward

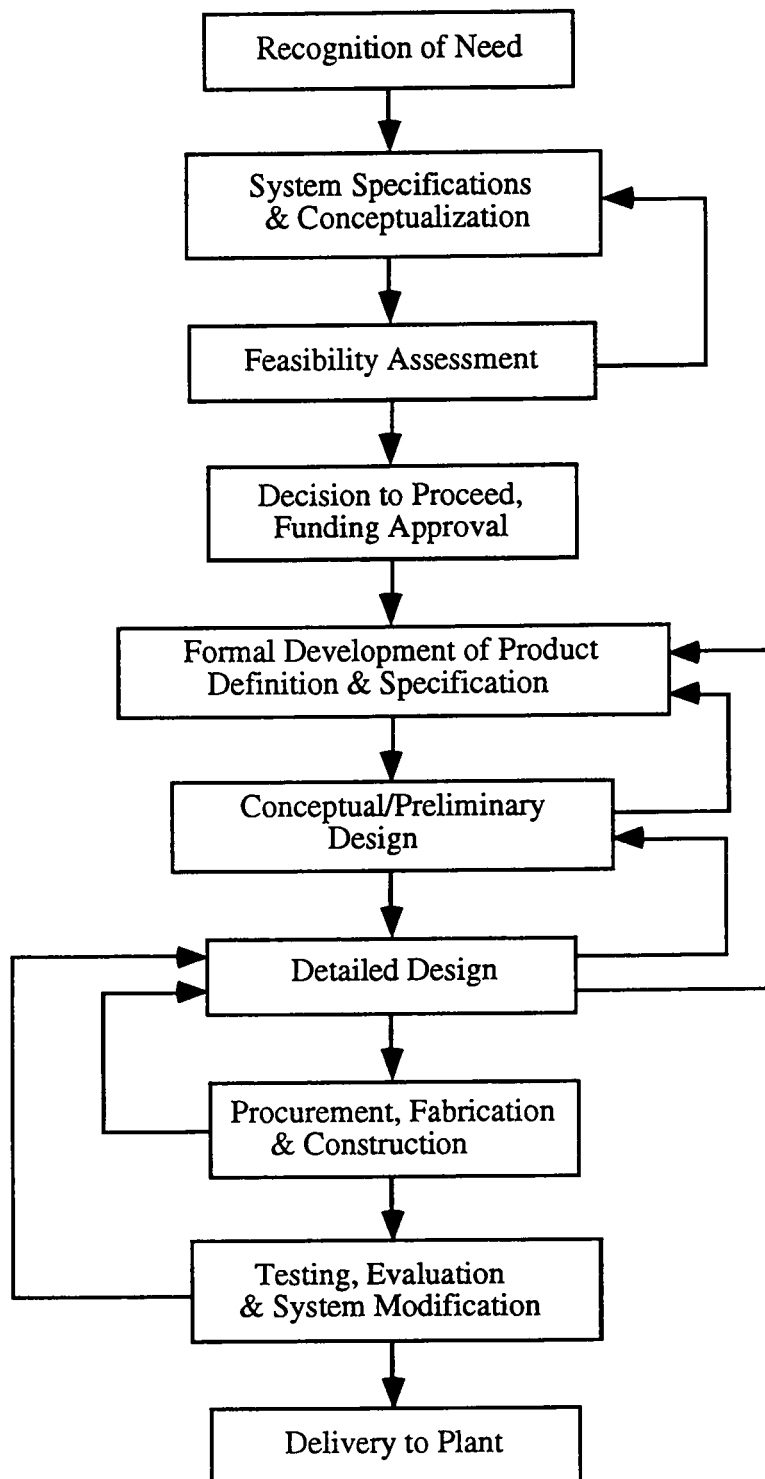


Figure 2.2.1 The Engineering Process Flow Chart Used for the Development of the Inspection Station Positioning Device

completion with the feedback lines representing design iterations and modifications. For each step in the design process, various requirements are needed in order for that step to be completed. Some of the basic requirements for each step is given as follows.

2.2.1 Recognition of Need

Typically the recognition of need is determined within the organization for which the design is to be completed. Whether by management or engineer, the recognition of need is establishment of a need for the design and value that recognition enough to proceed with the design. The decision to proceed will obligate the expenditure of funds until completion of the feasibility assessment, at which time negative results would terminate the effort. The recognition of need is essentially the birthplace of the design and begins the first phase of the design.

For this case, the recognition of need was determined by General Shale Brick Company as many employees were having medical difficulties in performing the de hacking process. In addition, the automation of this process would complete the already mostly automated process of manufacturing bricks.

2.2.2 System Specifications and Conceptualization

System specification and conceptualization establishes the basic ideas and goals of the design and to place these in some sort of framework. This step allows for both management and engineers alike to conceptualize the basic function of the design and integration requirements with the rest of the system. By establishing the integration requirements, system specifications and basic conceptualized design, the design can move into the feasibility assessment step of the design process.

2.2.3 Feasibility Assessment

The feasibility assessment stage of the design determines if the design as presently conceptualized can sufficiently meet the specified design requirements and specifications with economic considerations. The feasibility assessment typically involves engineering analysis, simulation work and sometimes testing of hardware that would be used in the design as currently conceptualized. Often, the feasibility assessment will require that modifications be made to the specifications of the design or that the conceptual design be modified. The feedback lines that represent this function can be seen in Figure 2.2.1.

For this project, the feasibility assessment was completed at the University of Tennessee in both the Electrical Engineering department and the Mechanical and Aerospace and Engineering Science department. The feasibility study completed is discussed in greater detail in Chapter Three.

2.2.4 Decision to Proceed & Funding Approval

The decision to proceed is the result of promising results from the feasibility assessment and an acceptable budget proposal for completion of the project. This step is essentially the end of the first phase of the design and establishes the termination or the continuation of the project. If continuation of the project is established, additional funding is required as the design moves into the next phase of the design.

2.2.5 Formal Development of Product Definition and Specification

The formal development of the product definition and specification is the step of the design process which sets the goals, specifications and basic requirements for the rest of the design process. This formal development of the product definition and specification is one of the most important design steps as it defines the goal of the project and outlines the specifications which the design must satisfy. For every specification given, the number of

possible solutions decreases rapidly which is generally good, but over specification can limit the design and hamper the creativity of the designer. It is here that the basic questions on the functionality, performance and system integration must be answered.

In Chapter Four, the system design requirements for this project are discussed in great detail and can serve as a guide for the development of similar documents in future projects. As shown in Figure 2.2.1, the product definition and specifications can be modified as the design progresses since unforeseen developments will undoubtedly arise.

2.2.6 Conceptual/Preliminary Design

The conceptual design is the most creative stage in the design of any product. Here the designer synthesizes various methods by which the goal of the project might be completed. At the completion of the conceptual design, the design will show the major components of the positioning device and how the components will function together, and the cost of the device will more or less be set. Usually ten to twenty percent of the project's funding is allocated for the conceptual design, but in the conceptual design, up to 75% of the projects funding is allocated based on the design selected. This shows the importance of a solid conceptual design and emphasizes the need to have a well thought out design.

The conceptualization stage includes the mechanisms, hardware, software, materials, etc. that can be used to develop a product or system by which the goal is met. This creative step can be among the most difficult and important in the development of a superior product or process as it will limit all future work within certain boundaries. The effectiveness of the conceptual design is basically a function of three factors:

1. The creativity of the designer,
2. The experience of the designer and
3. The length of time for conceptual consideration.

The creativity of the designer is a somewhat abstract entity since it requires that the designer be able to sketch out several methods by which the goal can be accomplished without having any preconceived judgment on what would or would not work. Dr. Frank Speckhart (a professor at UT in MAES) has stated in class discussions that creativity is a function of three factors:

1. Fearlessness of the engineer,
2. Openness to ideas and
3. Knowledge.

These creativity factors can gauge the creativity of the engineer and establish feasible creative designs. The experience of the designer allows for existing mechanisms to be employed for the completion of the project. Only by knowing what is out there and how it could be used for the given application can the designer develop an effective design. Typically, the designer will gather information on hardware and software that might serve as possible solutions to the problem. The time frame in which the designer has to develop alternative designs also plays a role in the final development of a superior product.

Typically for large systems, the system is separated into subsystems and subsystems into mechanisms and so on. This technique of breaking down the design into components allows for the design to be developed in a manageable manner that is not so overwhelming. Various components that have applicability for this project are presented in Section 2.3 under the title of Breaking Down the Design into Components.

The preliminary design is the continuation of the conceptual design for each of the alternatives and further develops the design to a point where analysis on the functionality and performance of the system can be completed. The analysis portion of the preliminary design is the most engineering-intensive step in the design process because it incorporates the analysis of thermal sciences, fluid flow, machine design, and controls for the mechanical engineering discipline alone. Additional considerations in electronics and electrical engineering only complicate the effort for the mechanical engineer. The analysis

of the design is the method by which the alternative designs are compared for the selection of the final design. Modeling, simulation, value analysis and basic machine design calculations are performed in the preliminary design stage. These tools allow for the design to be selected with respect to the system characteristics that are most important to the consumer. Modeling and simulation is discussed in greater detail in Section 2.4, and value analysis is discussed in Section 2.5.

2.2.7 Detailed Design

The detailed design is the continuation of the preliminary design for the design approach that has been selected in the preliminary design analysis. As the name indicates, the detailed design is the step where all of the system components as well as the overall system are designed in detail. Detailed CAD drawings are generated for the fabrication of the system components and careful analysis is performed on the system to verify that the design will satisfy the system requirements. In addition, commercial products integral to the design are identified and specified for procurement.

2.2.8 Procurement, Fabrication & Construction

The procure, fabricate and build stage of the design is where the system is put together to verify that all components fit correctly and interact properly with their environment. This step will typically begin in parallel with the detailed design because procurement and fabrication both have an inherent time lag before receiving the components for assembly.

2.2.9 Testing, Evaluation & System Modification

Once the system is assembled, the testing, evaluation and system modification stage of the design will begin. Here the system is tested for its adherence to the defined

specifications of the system. Evaluation on the functionality of the system is completed, and problem areas are recognized. System modifications to remedy the problem areas are completed and previous design stages are visited if necessary. Upon completion of this step in the design process, the design is ready for delivery to the plant and integration into the production lines for final testing and modification.

The positioning mechanism was developed using the presented design methodology, because it provided a means of staying focused on the next objective without becoming overwhelmed by the design of such a complex device. For nontrivial designs, having an outline such as the presented design methodology is necessary but not sufficient to ensure a good design. Technical exactness which is applied with the design methodology will, however, ensure a good design.

2.3 Breaking Down the Design into Components

As the design progresses, often it becomes necessary to break down the design into more manageable parts. This is true for both design and analysis, because smaller parts are much easier to deal with. In the development of the components that will make up the parts of the whole, it is important to focus on the overall performance and functionality of the system. The system is broken down into components in the conceptual design stage of the design as shown in Figure 2.3.1. After the components of the system have been designed and then determined to be acceptable, the components are organized back into the overall system. Special design measures are taken for adaptation into the system, and preliminary designs are developed. Once the most promising design alternatives are developed, the technically equivalent design sketches are analyzed, and the most promising alternative is selected. Once the design approach has been selected, the detailed overall design begins.

Since the mechanism that is being designed for this project is a camera positioning device for the inspection of brick, some of the basic devices that must be utilized in order to

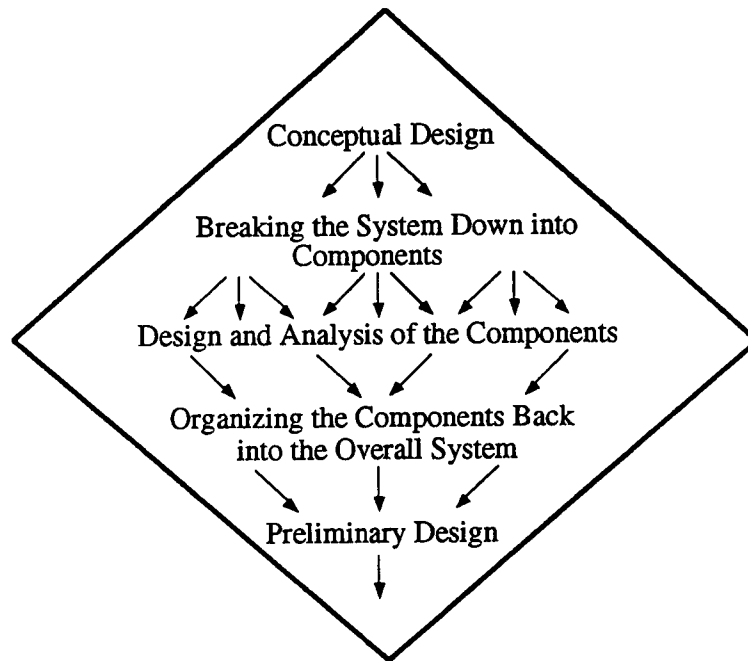


Figure 2.3.1 The Progression of the Design from the Conceptual Design to the Preliminary Design from Top to Bottom

realize the project goal can be recognized. A motion producing device or actuator must be used as well as some sort of transmission, path measurement system, bearings, couplings, software architecture, etc. These are some of the basic devices that must be implemented in any machine that must provide some sort of motion control. By taking a closer look at these devices component by component, devices can be selected that will provide the means of realizing the project goal. In the following sections, the basic devices that must be considered for a motion producing machine will be discussed with corresponding advantages and disadvantages of the device.

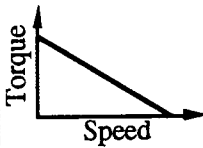
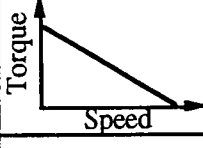
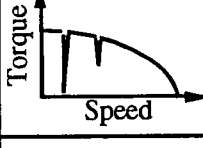
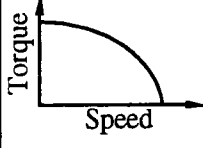
2.3.1 Actuators

Actuators are the means by which the system's motion is generated. There are three basic types of actuator devices. The first is hydraulic, second is pneumatic and third is electric. Each of these devices is discussed in Table 2.3.1.1 and Table 2.3.1.2. For

Table 2.3.1.1 Description of Basic Actuator Types

Type of Actuator	Description	Type of Motion Available	Advantages	Disadvantages
Hydraulic	Motion generated by fluid present in system. Fluid is typically oil or water based.	Translation and Rotation	High power to weight ratio, high accelerations can be realized.	Leakage problem and expensive
Pneumatic	Motion generated by compressed air.	Translation and Rotation	Inexpensive, good for open-close application	Position control is very difficult
Electric	Motion generated by electrical power with magnetic flux inducing motion.	Rotation and Translation	Good speed control, reliable and readily available power source	Moderately expensive, and power saturation

Table 2.3.1.2 Description of the Various Electric Actuator Types

Type of Electric Actuator	Characteristics	Advantages	Disadvantages
Brush Type DC Motor		Linear relationship between torque and speed, relatively low cost and good power-to-weight ratio for electric motor	Limited by thermal capacity and brushes and bearings will wear out
Brushless Type DC Motor		Linear relationship between torque and speed, no brush to wear out and better thermal characteristics	More expensive than brush type DC Motor and more difficult to implement (special controller required)
Stepper Motor		Relatively low cost, easy to control, open-loop position and velocity control possible, brushless and holding torque capability	Motor has resonance frequencies, power-to-weight ratio is low compared to other motors, and system can lose synchronization
AC Motor (3 Phase Motor)		Good power-to-weight ratio for electric motors, excellent for constant speed applications where speed controller is not required and brushless	Non-linear relationship between torque and speed, for speed control the frequency must be modulated (special controller required) and expensive

electric actuators, the device can be broken down into four different types: brush type DC motors, brushless type DC motors, stepper motors and AC motors. Within the electric actuator category, each of these types of electric actuators have their own characteristics as well as advantages and disadvantages. In Table 2.3.1.2, the various types of electric actuators are discussed in a tabular format.

2.3.2 Transmissions

For most motion producing machines, some sort of transmission is required. The transmission may simply transmit motion and power, or it may also scale the motion with speed reduction or speed amplification. A list of typical transmissions is given in Table 2.3.2.1 with the description of the device.

Depending upon the type of application the transmission will be used for, the following criteria should be considered [6]:

1. Transmission ratio and moments of inertia and size,
2. Bearing clearance and reversal error,
3. Weight,
4. Life and ease of maintenance and
5. Power transmission at a distance and movability.

2.3.3 Braking Systems

For vertical motion devices such as the mechanical positioner for the inspection station, braking systems are often required to maintain the vertical position of the device under static, failure or loss-of-power conditions. Therefore, the braking system is typically a normally closed system that is opened by electric or mechanical power. For the case of loss of power, the power to maintain the brakes in the open position is lost, causing the brakes to lock and maintain the position of the positioning device. While operating the positioner in the vertical direction, it may become necessary to brake the system when the positioner is to maintain a position for a specified time period dwell time. If left to electrical

Table 2.3.2.1 List of Typical Transmission Devices [6]

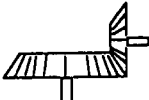
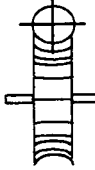
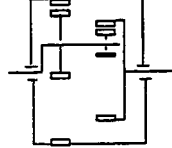
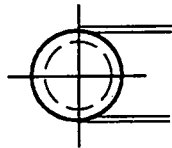
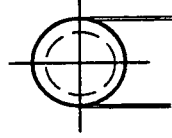
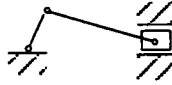
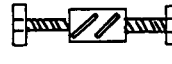
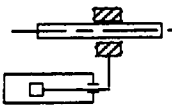
Type of Transmission	Principle	Characteristics	Transmission of Movement	Speed Reduction	Transmission at Distance
Spur Gearing		Very common, capable of high loads	Rotation to Rotation	Yes	No
Bevel Gearing		Transmits motion at 90 degree angle	Rotation to Rotation	Yes	No
Worm Gear		High transmission ratio, heavy in weight and heat problems	Rotation to Rotation	Yes, high	No
Planetary Gear		Expensive, heavy in weight and gearing is enclosed	Rotation to Rotation	Yes, high	No
Harmonic Drive		Very high transmission ratio, small dimensions, light in weight and low backlash	Rotation to Rotation	Yes, very high	No
Chain Drive		Low backlash, heavy in weight and no vibration	Rotation to Rotation, Rotation to Translation and Translation to Rotation	Possible	Yes
Toothed Belt Drive		Backlash and vibration problematic, very light in weight	Rotation to Rotation, Rotation to Translation and Translation to Rotation	Possible	Yes

Table 2.3.2.1 Continued

Type of Transmission	Principle	Characteristics	Transmission of Movement	Speed Reduction	Transmission at Distance
Bowden Wire		Very good for transmission on distance, axial extension	Rotation to Rotation, Rotation to Translation and Translation to Rotation	No	Yes
Four Bar-Linkage		Very good for precise power transmission on distance	Rotation to Rotation	Possible	Yes
Slider Crank Chain		Special case application, cyclic motion	Rotation to Translation and Translation to Rotation	No	Yes
Screw Drive Spindle		High transmission and friction (lubrication) problem	Rotation to Translation	Yes, High	Yes
Recirculating Ball Nut and Screw		High transmission, very high precision and reliability but expensive	Rotation to Translation	Yes, Very High	Yes
Toothed Rack		Precise, inexpensive but large dimensions	Rotation to Translation and Translation to Rotation	Yes	Yes
Cylinder		Many variations possible for hydraulic and pneumatic systems	Translation to Translation	Yes	Yes

actuators to maintain the vertical position, duty cycle and heat dissipation become areas of concern. There are various types of braking systems available to the designer, and some of these are summarized in Table 2.3.3.1. There are basically two types of fail-safe braking systems [7]. The first is the energy-absorbing or dynamic brake which decelerates the moving part until motion safely stops. The second is the static or parking brake which holds the position of the moving part while stopped. Almost all machines that have moving parts incorporate some sort of fail-safe braking system to protect the device.

Another type of braking system is the electric braking system which retards motion by magnetic flux forces. The electric brake works on the same principle as an electric motor but resists motion instead of inducing it. Electric brakes are not fail-safe brakes because power failure will disengage the braking system.

2.3.4 Position Measurement Systems

Position measurement systems are used as devices to generate feedback for use in the closed-loop servo-control of most actuators. These devices will typically generate data that can be used to track the position, speed or acceleration of the actuator. By including position measurement systems in the design of motion producing machines, the command given by the controller will initiate motion until the feedback given from the position measurement system is in correspondence with the commanded instruction. Table 2.3.4.1 shows a list of some of the common types of position measurement systems with some of the characteristics of each.

2.3.5 Controller Systems

The controller system which will ultimately control the mechanical device has a great impact upon the overall performance and durability of the machine. The controller can in fact "make or break" a design. How the controller is organized to handle exceptions

Table 2.3.3.1 Types of Fail-Safe Braking Systems [7],[8]

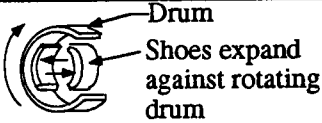
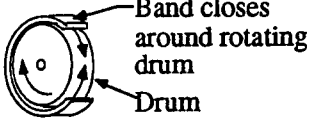
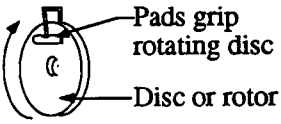
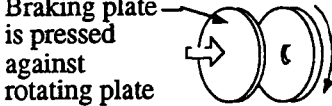
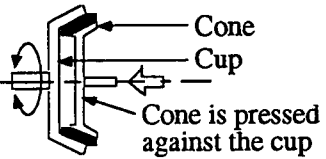
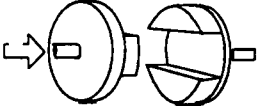
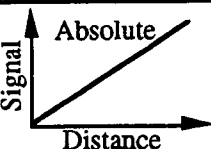
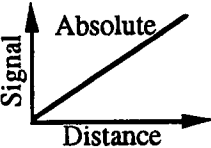
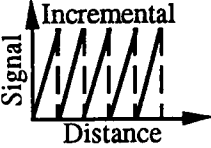
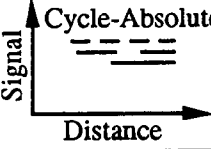
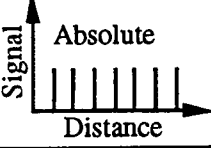
Type of Braking System	Principle	Characteristics
Drum		The drum type brake is well established especially in the automotive industry. Relatively high resistive force capabilities with low heat dissipation capabilities. Fairly expensive and complex to build. Uneven wear and self locking.
Band		The band brake is a simple design with low resistive force capabilities and average heat dissipation capabilities. Low cost and typically used as parking or static brake.
Disc: (Caliper)		The disc braking system which uses the caliper pad is a common braking system. Self-cleaning, high resistive forces, and excellent heat dissipation make the caliper system popular. Requires high actuation pressure and often requires some sort of power assist.
Disc: (Plate)		The disc braking system which uses plates can produce high braking forces in a small package but has poor heat dissipation capabilities and tends to overheat if cycled frequently.
Cone		The cone braking system is not widely used but can produce exceptionally high resistive torque for a given applied force. It is difficult to control torque and to disengage brake once brake is engaged.
Mechanical Interlock		The mechanical interlock braking system is a static or parking brake. Not an energy absorbing braking system but can hold the position of the moving part after it has stopped even under extreme loading conditions.

Table 2.3.4.1 Types of Position Measurement Systems [6]

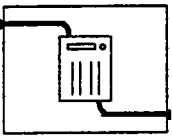
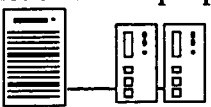
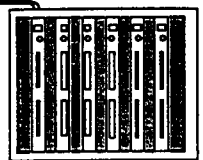
Type of Path Measurement System	Data Register	Reference Point	Advantage	Disadvantage
Potentiometer (Analog)		Fixed	Inexpensive and small dimensions	Linearity, contact measuring and mechanical uncertainties
Ultrasound (Analog)		Fixed	Long translatory measuring range and direct measuring method	Expensive and difficult data processing
Resolver (Analog)		Ambiguous	Robust, simple design and resolver inexpensive	Digitization of signals, expensive and data ambiguous
Absolute Encoder (Digital)		Fixed	Unambiguous representation of shaft angle, high resolution and no additional errors	Limited measuring range or very expensive
Incremental Encoder (Digital)		Ambiguous	Unlimited measuring range, inexpensive and simple design	Addition of errors, revolution marker necessary and disturbance pulse control

and abnormalities has great influence on how the consumer believes the product performs. Therefore, it is essential to at least consider the controller architecture of the motion device while still in the conceptual design stages of the design. Table 2.3.5.1 outlines some of the basic controller options available to the designer and their corresponding characteristics.

The controller system can be any one of the architectures shown in Table 2.3.5.1 or any combination of the architectures. Combinations of the microcomputer and the PLC systems can constitute cell (or distributed) control systems which have a hierarchy approach to controlling the system [7].

When evaluating motion control boards, an important consideration is whether the boards provide special I/O normally used in motion control. Some typical I/O found in

Table 2.3.5.1 Types of Controller Systems [9]

Type of Controller System	Principle	Characteristics
PLC Environment	Input  Output	The PLC environment allows for I/O cards, motion control cards, etc. PLC's are very well established for industrial applications because they are rugged and robust. Primarily a logic controller with secondary function as motion controller. The PLC uses ladder logic.
Industrial Microcomputer Package (PC based)	Industrially hardened computer with motion control peripherals 	The industrial microcomputer package controllers are extremely versatile and easy to implement. Primary function would be motion control and secondary function as logic controller. Also well established in industrial applications but more expensive than PLC's and software can be overly complex. This architecture includes ISA, EISA, and PCI standard PC bus structures.
Integrated Industrial Modules (bus architecture)	 Modular cards fit into back-plane	The integrated industrial modules are extremely versatile and modular. The modularity allows for the controller to be fitted to the application to minimize the computation requirements, but it also maximizes the integration requirements on the user. Although the computational requirements can be reduced, the cost per card is very expensive. The backplane of the bus architecture has a very high data transfer rate which is suited for high data transferal applications.

motion control is a drive-fault input, drive-enable output, negative overtravel input, home input, positive overtravel input, and differential and single-ended encoder inputs [7]. The servo software should be set up to scan these critical inputs approximately once per millisecond while the servo-loop runs [7].

2.3.6 Bearings and Guideways

For most cases, the bearings and guideways of the system will be under high loading conditions. Low bearing clearances should be maintained in order to keep positioning, reversal and trailing error to a minimum.

2.3.7 Couplings

Couplings which are not properly suited for a particular application can cause serious problems if carelessly selected by the designer. When considering which type of coupling to select, the following requirements should be reviewed:

1. Keep the reversal error as low as possible,
2. Limit the weight of the couplings and restrict the technical expenditure,
3. Reduce vibration and overloading in the drives, and
4. Keep the system as low maintenance as possible.

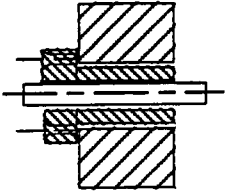
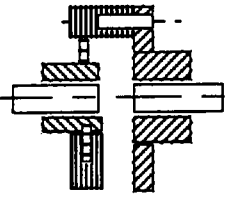
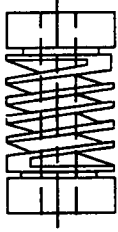
Table 2.3.7.1 shows some of the commonly used couplings and gives discussion on example applications for the respective coupling.

2.4 Modeling & Simulation

In order to analyze a physical system, it is essential to model the system in such a way that the model correctly demonstrates the behavior of the physical system. The model can take many forms, such as mathematical model, prototype model, scaled model, etc. Only by properly modeling the physical system and understanding what is actually taking place in the physical system can the designer develop a design to meet the project goals. Once the components that apply have been selected, investigation into the details of how those devices function is essential for proper modeling to be completed. Mechanical engineers have a broad background with statics, dynamics, physics, materials, machine design, controls, thermodynamics and fluid flow which allows them to perform modeling on many devices by intuition, scientific principles and experience.

Once the device has been properly modeled, analysis is completed to determine the characteristics of the device which account for the performance and functionality goals of the project. First, the individual components are modeled for analysis, and then the components are organized into the system as a whole so that modeling of the entire system can be performed.

Table 2.3.7.1 Commonly Used Types of Couplings [6]

Type of Coupling	Principle	Example Application
ETP-bush		Typically applied for applications with smaller forces with the possibility of misalignment between the shaft and hub. By means of a hub, the pressure applied is distributed along the hub with constant pressure. A high torsional moment can be carried by the ETP-bush.
CENTAFLEX-coupling		Excellent for applications where thermal expansion is involved. Compliant in axial and radial directions but very rigid in torsion. Shafts can be out of alignment and coupling will still operate effectively.
HELICAL-coupling		Coupling most applicable with changing moments and oscillatory vibrations in the system. The HELICAL coupling is able to transmit a regular rotation at very high speeds without reversal error. Often, such a coupling is used between the drive and the path measurement system.

"Simulation involves subjecting models to various inputs or environmental conditions to observe how they behave and thus explore the nature of the results that might be obtained from the real-world system. Simulation is only the manipulation of the models" [4]. Simulation can be performed by testing the prototype or scaled models which have been developed or by computers which involve mathematical disturbances being given to the mathematical model. An example of simulation testing would be the application of using MATLAB or SIMULINK [10] for simulation of the control response for an electrical actuator given a specified input.

2.5 Value Analysis

As components are gathered into design alternatives as possible solutions to the project goal, it is necessary to have some mechanism by which the most suitable alternative

can be selected. This mechanism of finding the best alternative is the process of value analysis. In value analysis, the design considerations that apply to the design are given weighting values, and the alternative which best suits the design criteria is selected. In any design, particular design considerations will have a greater impact on the eventual success of the project. Therefore, those design considerations are given a higher weighting value. Some of the design considerations which are encountered in design of motion producing devices are given in Table 2.5.1.

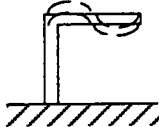
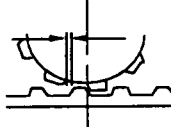
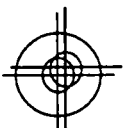
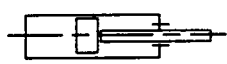
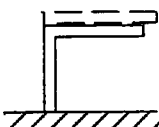
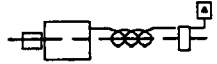
Table 2.5.1 Design Considerations [11]

General Considerations	Manufacturing Considerations	Technical Considerations
Reliability	Processing	Strength
Flexibility	Styling	Thermal Properties
Maintenance	Shape	Corrosion
Liability	Size	Wear
Cost	Surface Finish	Friction
Safety	Machinability	Control
Utility	Weight	Stiffness
Life	Time to Build	Noise

In addition to the design considerations given in Table 2.5.1, the selection of the best alternative must also take into account national or regional codes or standards which might place additional requirements upon the system.

Another consideration in determining the best alternative for the application is the recognition of the weak points in the design which might pose a problem to the system. A list of the most common weak points present in mechanical design are presented in Table 2.5.2.

Table 2.5.2 Weak Points in Mechanical Systems [6]

Weak Points	System	Measures to be Taken	Calculation Method
Deformation of the total structure and single components		Increase stiffness, reduce weight of the structure and counterbalance	Finite Element Method (FEM)
Dynamic deformation		Increase stiffness, reduction of masses in motion and distribution of masses	Frequency and time related methods
Backlash		Reduce backlash in gearing and use a stiff power transmission system	Experience of the component manufacturer
Bearing clearance		Prestress bearings	Experience of the component manufacturer
Friction		Increase bearing clearance and improve lubrication	Experience of the component manufacturer
Thermal effects		Isolate heat source	Finite Element Method (FEM)
Path measuring system		Depends on the system location and connection with the mechanical system	Experience of the component manufacturer

By analyzing the alternative designs on the basis of meeting the project specifications with special consideration to other design factors, the optimum design is selected for continuation. Experience of the designer and knowledge of the wants of the consumer aid the designer in selecting the best suited design.

2.6 Summary

The design of a new product or process is a methodical process which incorporates many facets of the engineering profession. The design process shown in Figure 2.2.1 shows the design methodology used in the development of the positioning device for the brick inspection station. Discussion on the steps taken throughout the progression of the design is given with special consideration given to breaking the system down into components, modeling and simulation, and value analysis.

Chapter Three

Feasibility Study Results

3.1 Overview

The feasibility study for the possible development of an automatic dehacking system to perform the task of unloading, inspection, blending and packaging of brick from kiln cars was completed fall of 1994. The purpose of the study was to investigate if robotic or automated systems could be developed to perform the task of automatically dehacking brick while meeting production rates required in a present brick manufacturing facility. While performing the dehacking task, the system would singulate the bricks, inspect the bricks for cracks, and also perform blending to ensure that a superior bundle of bricks leaves the plant. In particular, the possibilities of robotic dehacking and computer vision inspection were investigated as possible solutions to General Shale's needs.

The feasibility study was performed at the University of Tennessee, Knoxville, as a joint venture for the Mechanical and Aerospace Engineering and Engineering Science department and the Electrical Engineering department. The MAES department had the responsibility to investigate the feasibility of an automatic dehacking system which could replace the present manual operation. In order to accomplish this task, the MAES group would perform a demonstration of a robotic solution to the dehacking process while also developing a conceptual design of a robotic system that could be implemented at the Corbin, Ky., brick manufacturing facility. The EE department had the responsibility to investigate the feasibility of an automatic inspection facility utilizing vision-based technologies. To accomplish this study, the EE group performed a demonstration of an on-line vision-based inspection station for bricks being transported on a conveyor line.

Classification of "bad" brick based on the observation of cracks 2 mm or greater was the objective of the EE group.

3.2 Approach and Scope

The feasibility demonstration for robotic dehacking was separated into two major areas. The first, brick unloading and handling, was assigned to the Mechanical and Aerospace Engineering and Engineering Science Robotics Laboratory. The MAES group was comprised of Dr. Bill Hamel, Jeff W. Buck, Angela Gizelar and Karen Bills. Dr. Hamel was responsible for the completion of the overall project goal while I worked on the robotic dehacking demonstration and Angela and Karen developed the IGRIP simulation for the project. The second, brick inspection, was assigned to the Electrical and Computer Engineering Image Processing Lab. The EE group was comprised of Dr. Mongi Abidi, Mike Lipscomb, Heath Brewer and Eric Lester. Dr. Abidi, Mike, Heath and Eric collectively developed the computer algorithms and project demonstration for the vision-based inspection system.

The general approach for the feasibility demonstration was for both of the laboratories to do their respective tasks separately while working together enough to ensure cohesiveness.

3.2.1 Brick Unloading

The brick unloading and handling portion of the demonstration was accomplished through two interrelated tasks. The first task was to use the available equipment in the MAES department to simulate the basic steps on the dehacking process. The second task was to develop a conceptual design which would offer the preliminary concepts and alternatives for the actual production system.

For the first task, it was proposed to accomplish the study objectives by using a robot system available in the MAES department to simulate the basic steps in the dehacking process. In addition to studying the motions that would be required from the dehacking robot, the general characteristics of the bricks as they interact together when sitting on the bung were also studied. The scenario that the demonstration followed was developed jointly with General Shale to assure that it meets their requirements for realism and relevance. For this demo, an IBM 7547 planar robot was used to dehack a portion of a sample bung. The bung matched the exact dimensions of the actual bung used at the Corbin, Ky., plant, although its height was modified for the demonstration due to the restrictions of the robot used. Other limitations of the IBM robot were a payload capacity of 20 kg including the end-effector weight and sequential motion that limits the overall time of a dehacking cycle. Still, the IBM robot was adequate to demonstrate the basic kinematic steps required for dehacking and provide a reasonable approximation to the handling cycle times necessary.

The second task was a conceptual design effort to provide an initial investigation into the design alternatives, particularly in the area of the robot manipulator systems, which are applicable to the actual production requirements. This task was demonstrated by utilizing a 3-D graphical modeling software package (IGRIP) that would show the basic requirements for a robotic solution to the dehacking problem.

3.2.1 Brick Inspection

The brick inspection portion of the feasibility project was investigated in the Image Processing Laboratory in the Electrical Engineering department. By using available image processing equipment and software, single bricks from General Shale were analyzed under simulated plant lighting conditions. The first task was to evaluate various feature extraction

algorithms in terms of their ability to detect various flaws. The next task was to concentrate on the fine tuning and evaluation of the most promising technique.

Once the technique and equipment were decided upon, the system was developed and tested. The testing was conducted with actual bricks provided from General Shale. For this project, one brick at a time was studied while it moved down a conveyor belt to determine if the computer-vision system could accurately distinguish between good and bad bricks. Bad bricks were defined as bricks with cracks greater than two millimeters. All bricks were inspected by a human examiner in order to determine if the computer-vision system was accurate.

3.3 Objectives for the Brick Unloading Demonstration

The robotic dehacking demonstration was incorporated into the feasibility study in order to determine if a robotic system limited to five or six robots could dehack bricks at the plant's desired output rate. Currently, the Corbin, Ky., plant produces approximately 30,000 bricks per hour. Such a production rate would indicate that the robotic dehacking machines would have to operate at a rate of approximately 6000 bricks per hour with five robots and 5000 bricks per hour with six robots. This study determined that five or six robot stations in parallel could successfully move at such a rate while dehacking a bung.

3.3.1 Technical Approach and Equipment for the Brick Unloading Demonstration

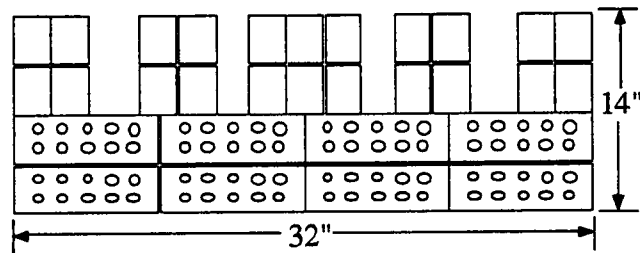
The IBM 7547 industrial type robot was used as the test bed for the demonstration. The IBM robot operated at speeds that would be comparable to the speeds that the actual dehacking robot would move and also had the necessary degrees of freedom to perform such a task. The limitations of the IBM robot for such a task were its 20 kg maximum payload capacity, limited workspace, exclusively sequential motion and a 10 inch span of

motion in the z-axis which provides the lift motion for the robot. The demonstration was developed to work around these limitations, but the realism and results of the demonstration were not diminished.

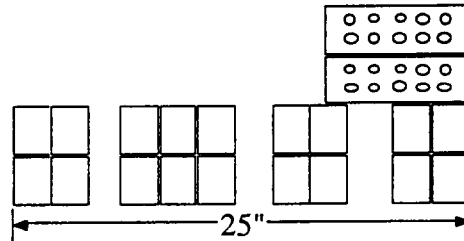
For the demonstration, the robot system grasped either four or six bricks simultaneously from the kiln car bung depending on the row location of the cycle. The robot performed a series of sequential motions as it went through a cycle. A typical cycle included moving the end-effector over the bricks to be grasped, lowering the end-effector, grasping the bricks, raising the bricks, moving the bricks over the conveyor set down point, lowering the bricks, releasing the bricks, raising the end-effector and grasping the top row of the bricks, raising the top row of bricks, moving the conveyor belt, lowering the top layer, releasing the top layer of bricks, raising the end-effector and moving the conveyor belt, and finally returning to the next brick set position. For this demonstration, the locations of the brick sets were assumed to be known so that no on-line corrections had to be made when the robot went to grasp the bricks from the bung. Since the actual gripper that would be designed would grasp entire rows of brick, no on-line corrections were necessary to account for alterations in the position and orientation of the bricks in the bung. A continuation of this study would be to incorporate sensor feedback so that on-line corrections could be made for skewed or fallen brick. Such an application would be for robotic restacking of the skewed or fallen brick prior to the deacking process.

The sample brick pallet was developed from the actual dimensions of the bungs at the General Shale Brick Corbin, Ky., manufacturing facility, but the bung was modified to fit the limitations of the robot used for the demonstration. The sample brick pallet that was used can be seen in Figure 3.3.1.1.

The layout for the demonstration was in correspondence with the preliminary conceptual design that General Shale developed, as seen in Figure 3.3.1.2. The system included a series of five or six parallel conveyor lines that would have a robot for each line



Front View



Side View

Figure 3.3.1.1 Sample Pallet for Dehacking Demo

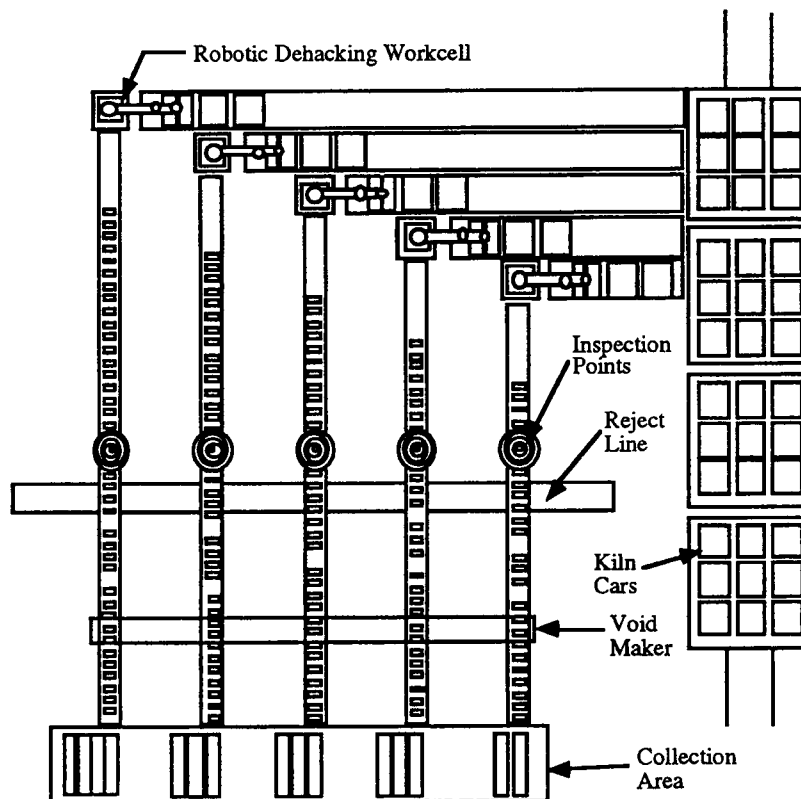


Figure 3.3.1.2 The Conceptual Design of Complete Robotic Dehacking System

to dehack the bungs delivered from the kiln cars. Once the bricks were singulated, the conveyor lines carried the bricks through the inspection points where the computer-vision inspection was performed. The bricks were then carried through the rejection points, void makers and finally to the collection area. The robotic dehacker would be located between the bung conveyor that carried bungs from the kiln car to the robot and the conveyor that carried the singulated bricks through the inspection points. The demonstration layout was developed to show the robot dehacking several coarses of the bung from the bung conveyor to the singulated conveyor that would transport the bricks to later inspection points as seen in Figure 3.3.1.3.

The equipment used for the demonstration included the IBM 7547 robot and controller, Zatrane pneumatic gripper model GPL-200, MAC solenoid valve model PME-611CAA and a TORQube 12 foot conveyor belt. The IBM robot controller was programmed using the AML (A Manufacturing Language) computer language developed for use with the IBM robot. Figure 3.3.1.4 shows the IBM robot in the process of dehacking the sample pallet while utilizing the above stated equipment.

The computer program used to perform the necessary motions to perform the dehacking task was developed at the University of Tennessee Mechanical and Aerospace Robotics Research Laboratory. The program initiated a series of sequence motions that dehacked the sample pallet by moving through twenty-one pickup positions on the bung. Every one of the twenty-one cycles was composed of a series of locating, grasping, moving to set-down location and releasing sequence. The AML computer program developed can be seen in Appendix A.

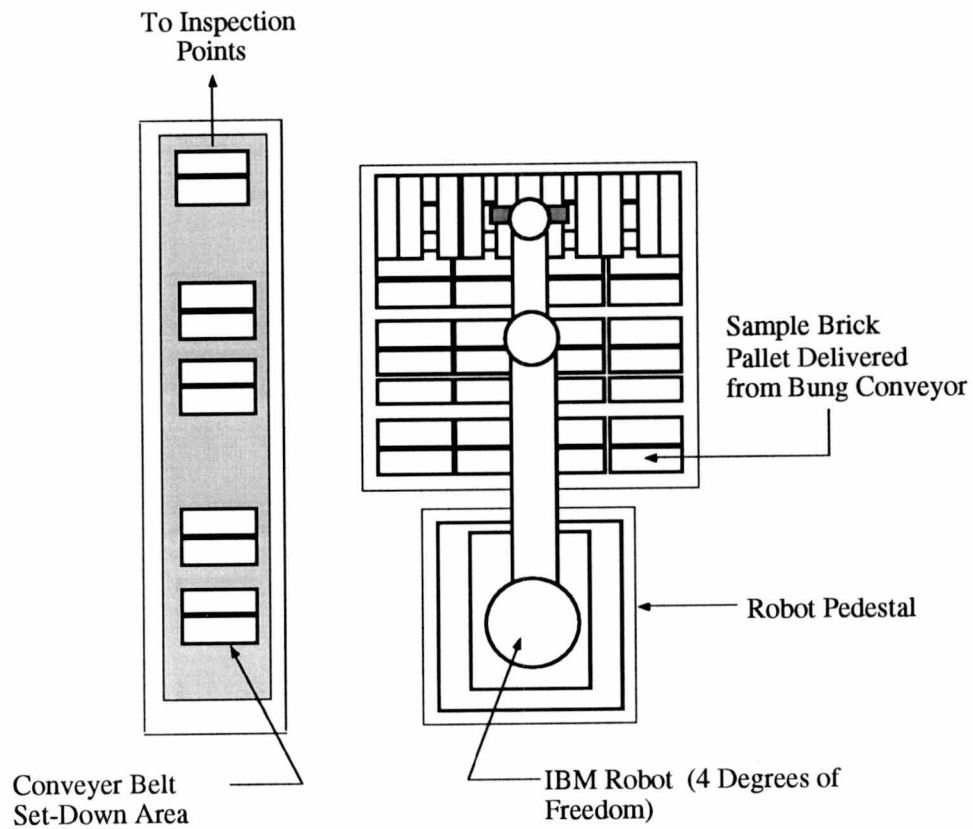


Figure 3.3.1.3 Layout of Robotic Brick Dehacking Demonstration

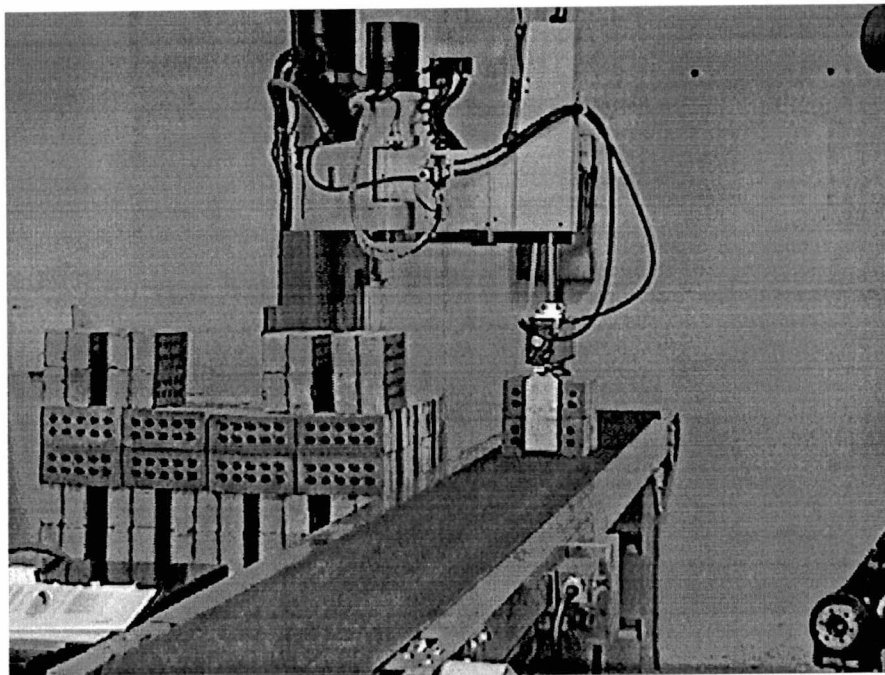


Figure 3.3.1.4 IBM Robot Dehacking Demonstration

3.3.2 Results from the Brick Unloading Demonstration

The dehacking demonstration provided encouraging results for the future implementation of robotic dehacking systems. The demonstration system moved a total of 94 bricks in approximately four minutes and fifty-five seconds while moving through twenty-one cycles. The twenty-one cycles were necessary because only four or six bricks at a time were being grasped due to the limitations of the robot. The average cycle time over the twenty-one cycles was approximately 13.8 seconds per cycle. This cycle time corresponded to a rate 1150 bricks per hour while grasping only four or six bricks at a time.

In the actual robotic dehacking system, the robots would grasp twenty two bricks at a time for standard and modular size brick. At the rate of twenty two bricks per grasp, the results from the experiment would be comparable to approximately 5735 bricks per hour per robot. With five robotic dehacking system running at the resulting rate, the system would have an output of 28675 bricks per hour while operating at 100% capacity.

3.3.3 Conceptual Design for a Robotic Solution to Unloading Brick

The conceptual design for a robotic solution for unloading brick was developed in accordance with the preliminary system design developed by General Shale as shown in Figure 3.3.1.2. The robots that would perform the unloading of the brick would each require a minimum of 4 DoF and would need a workspace large enough to perform the task of unloading bricks from the bung and placing the brick onto the conveyor line at an angle from the bung conveyor line of 90°.

It was determined that the bungs delivered from the kiln cars would be broken down into halves. Therefore, the depth of the workspace would be the height of half a bung, or four coarses high with each coarse about seven inches high. The bung is

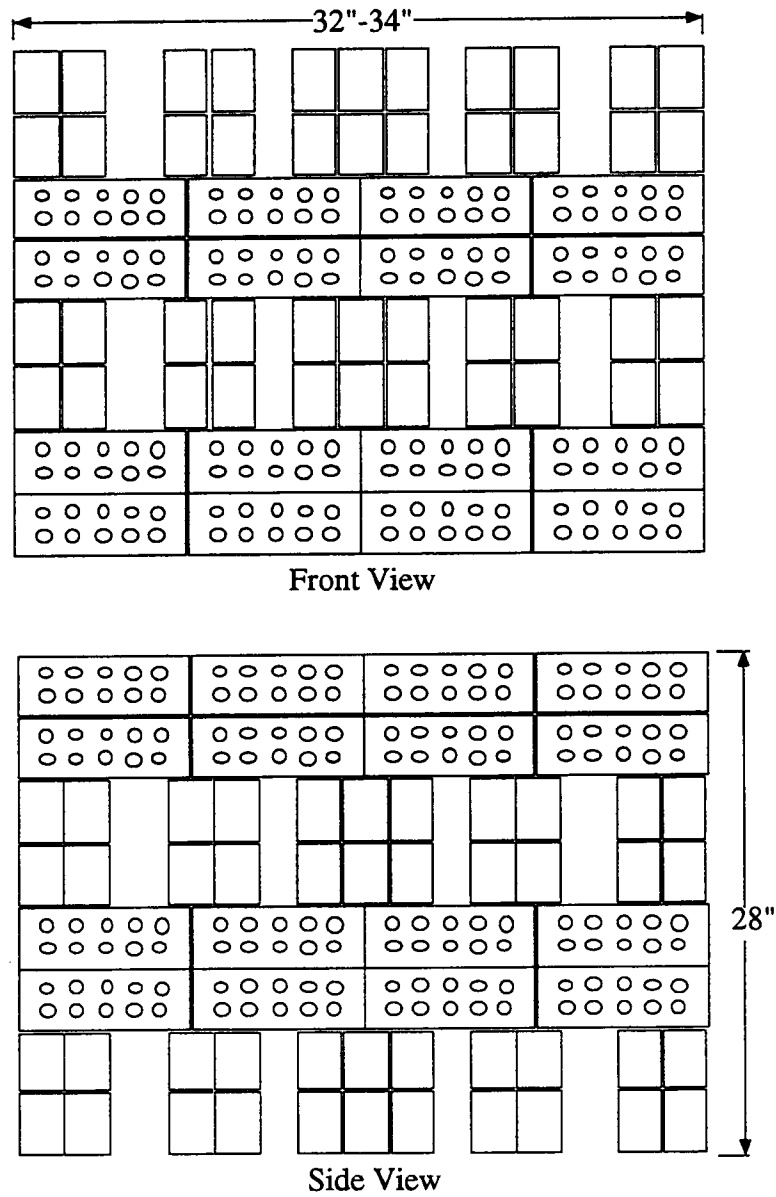


Figure 3.3.3.1 Bung to be Delivered to Robot for Dehacking

approximately 32 to 34 inches wide and long as seen in Figure 3.3.3.1. The robot will dehack the delivered bung by grasping 22 bricks at a time (22 bricks comprise one row at two courses high) and swinging over to the downstream conveyor to place the bricks. The robot must have a payload capacity of approximately 85 pounds to lift the 22 bricks while de hacking.

A 3-D graphical computer simulation of the brick de hacking system was created to aid in the conceptual design of the robotic de hacking system [12]. The simulation was developed using IGRIP (Interactive Graphical Robot Instruction Program) software on an Indigo2-Extreme Silicon Graphics workstation. The IGRIP model of the conceptual robotic de hacking system that was developed for actual plant implementation is shown in Figure 3.3.3.2.

The simulation contributes to the design process by illustrating the operation of the system before fabrication of any part of the design. If any problem is encountered with the operation of the system as a whole or with any one of its parts, the design or configuration of parts within the system can be changed in the simulation. The simulation can also be used to determine cycle times needed and to explore different camera angles that would be used in the inspection of the bricks.

The layout of the simulation was in correspondence to the preliminary conceptual design that would incorporate five robotic stations to dehack the bung halves as delivered from the kiln cars. The conceptual design shown in Figure 3.3.3.2 represents one of the five robotic stations that would comprise the entire system as laid out in Figure 3.3.1.2.

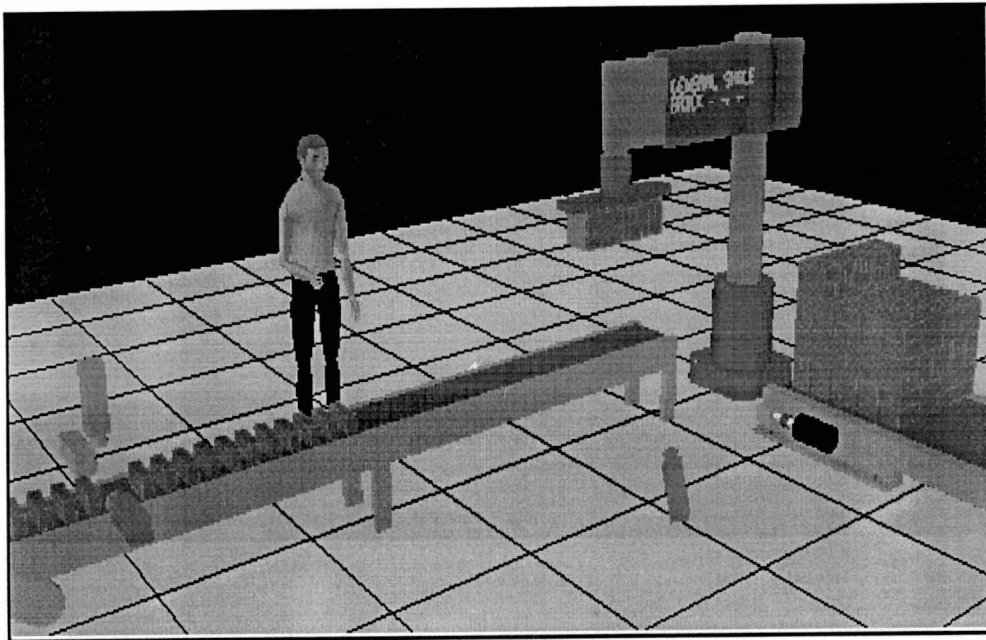


Figure 3.3.3.2 3-D Graphical Simulation in IGRIP [12]

The results from the conceptual design study indicate that a 5 DoF robot with only moderate accuracy and repeatability could successfully perform the dehacking process. To accomplish the robotic dehacking, a custom design with a simpler design than off the self robots would offer performance and cost advantages although off the self robots are available to suit such an application.

3.4 Objectives for the Computer Vision-Based Inspection

The objective of the feasibility study was to develop a system that would aid General Shale in the inspection and classification of brick samples. For the feasibility assessment stage of the project, the EE group developed algorithms for the inspection of brick in order to detect crack defects 2 mm or greater [2].

The computer-vision inspection system was developed for use in some type of automated system that would bring singulated bricks through an inspection area where the vision-based inspection would be done. The bricks would be inspected while traveling on

a conveyor belt, and for this study, the brick were inspected one at a time with only the bottom face of the brick being inspected as shown in Figure 3.4.1.

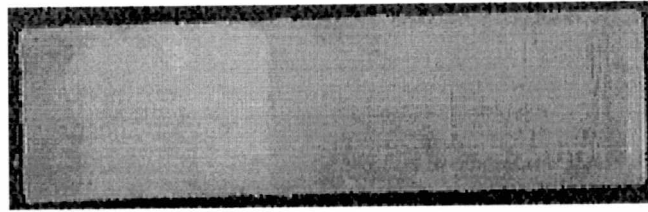


Figure 3.4.1 Brick's Bottom Face [2]

3.4.1 Technical Approach and Equipment for Computer Vision-Based Inspection

Video camera equipment already available in the Image Processing Laboratory in the EE department was used to implement image analysis algorithms for the detection of cracks present in brick as shown in Figure 3.4.1.1.

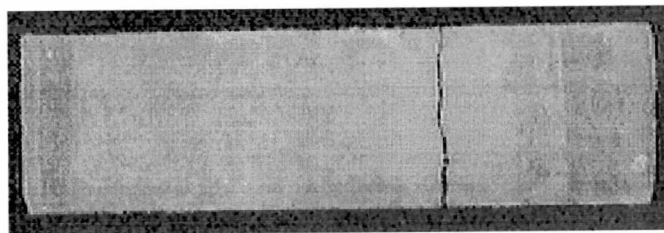


Figure 3.4.1.1 Cracked Sample [2]

There are basically two approaches for detecting cracks. The first approach is to generate a one-dimensional signature of the brick, complete with valleys that represent the crack as shown in Figure 3.4.1.2. A classification of the brick is based on the presence or absence of valleys that are considered to be cracks in the brick. The second approach is to develop a two-dimensional image that would represent the inspected side as shown in Figure 3.4.1.3. This image would undergo several image processing steps, producing a

final image from which the computer could make a decision. This image should show a white crack clearly on a black brick background.

Development of the one-dimensional signature is closely tied to the use of a laser range scanner for crack inspection. It is possible to have a laser "sheet" that can scan the entire surface of the inspected brick face and generate a one-dimensional signature. This laser sheet can use the natural motion of the conveyor belt to generate a continuous "sampling" of the inspected brick face. Once a collection of samples is generated, operations (averaging, summation, root-mean-square, etc.) can be applied to reduce the collection of samples to a single signature.

The use of the two-dimensional image processing system was the area of concentration for the EE group since the video camera was available. The camera was used to generate a library of brick samples which would act as a template for the inspection process, and then start performing image processing functions on this library in order to test the image analysis algorithms [2].

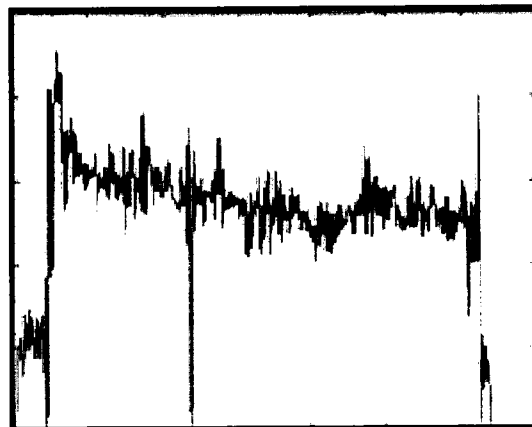


Figure 3.4.1.2 One-Dimensional Signature [2]



Figure 3.4.1.3 Two-Dimensional Signature [2]

3.4.2 Testing Procedure for the Computer Vision-Based Inspection

In order to analyze the brick samples, a systematic approach was followed to complete the inspection process. An outline of the steps taken to classify the brick are given as follows [2]:

1. Obtain the image from the video equipment in .gif format.
2. Convert a library file from .gif to .ppm format.
3. Convert the .ppm format file into separate red, green, and blue channels to simulate the channels of a video camera.
4. Isolate the brick in the image by summing horizontal pixels to obtain a horizontal signature, adding the vertical pixels to obtain a vertical signature. Then bound the brick against the background by comparing the signatures against the background, and output the final image file. (Errors caused by this step are due to the fact that the isolation algorithm is not completely adaptive. The internal values used for the signature brick/background thresholding are constants. To significantly reduce the occurrence of isolation errors, an adaptive algorithm can be created to generate isolation values unique to each image.)
5. Threshold the brick image. Each horizontal line of the brick image is broken into small segments, the size of which is an internal constant. These segments are then thresholded by computing each

pixel's deviation from the segment's average intensity. The maximum deviation from the average segment intensity has a constant scale factor. An adaptive generation of the segment size and the deviation scale factor could increase performance significantly.

6. Classify the brick as good or bad. We manually classified our library as good bricks or bad bricks based on the presence or absence of cracks. Once a brick was classified, it was noted as falling into one of four categories:

A. GOOD classified as GOOD

B. BAD classified as BAD

C. GOOD classified as BAD

D. BAD classified as GOOD

The vision system classifies brick by searching the thresholded image for crack segments of a predetermined size. If any segments are identified, the brick is considered cracked and classified accordingly. Currently, only vertical segments are identified, but a considerable improvement could be gained by developing an algorithm to search for crack segments of any orientation.

3.4.3 Conclusion for Computer Vision-Based Inspection

The results obtained from the vision-based classification of bricks was very promising. A total of 92 brick were inspected and classified using the image analysis algorithms developed at the Image Processing Laboratory. The results of the brick classification testing are outlined in Table 3.4.3.1.

Table 3.4.3.1 Results from Brick Classification Testing [2]

Brick Type (as specified by GSB)	Inspection System Classified	Inspection System Classified
	Good	Bad
Good Brick	94% (63 out of 67 brick)	6% (4 out of 67 brick)
Bad Brick	8% (23 out of 25 brick)	92% (2 out of 25 brick)

The results from the feasibility study also led to the conclusion that it is realistic to design a vision system with the following characteristics [2]:

1. Inspection of 5000-6000 bricks per hour per conveyer line.
2. Detection of line flaws on the order of 2 mm width (average width of our cracked samples).
3. Detection of pits, chips, and color variations of reasonable size and diversity.
4. Computer hardware kept to a minimum using components now available.
5. Modular image acquisition hardware using off-the-shelf parts to facilitate easy repair and minimize downtime.

The development of an inspection station for use in brick manufacturing facilities is very realistic and has short-term applicability.

3.5 Overall Feasibility Study Results

The conclusions drawn from the feasibility study concerning the robotic dehacking of brick and the visual inspection of brick were very positive and show near term applicability in the harsh environments of brick manufacturing facilities. With further research, both the robotic dehacking and vision-based brick inspection station could be implemented into a General Shale manufacturing facility in the next couple of years. From the results of the feasibility study, General Shale has expressed optimism and the interest in

extending the research effort to the working implementation for both a robotic dehacking and vision-based inspection system for the technological advancement of their brick manufacturing facilities.

General Shale has decided to implement these systems in steps and has chosen to implement the vision-based inspection station first. The inspection station will be used in conjunction with a hard automation dehacking system (the BUPS) as designed by ARTECH. It is the design, fabrication and implementation of the vision-based inspection station that this thesis explores and develops. In future research efforts, the design and development of the robotic dehacking approach will be investigated.

Chapter Four

System Design Requirements

4.1 Overview

This chapter on the system design requirements (SDR) for the inspection station will highlight the goals and requirements of the 1-D vision based inspection station for the inspection of brick. This chapter will define the mechanical and electrical requirements for the inspection system as well as give other general information that is pertinent to the performance of the system. The development of the SDR is in accordance with specifications as documented by ARTECH [13] and General Shale Brick [14]. The inspection system will be integrated after completion of the new brick dehacking system that is being designed by ARTECH, and therefore system integration considerations are addressed as well as design requirements.

Currently, the General Shale Brick plant in Corbin, Ky., produces approximately 30,000 brick per hour. With the incorporation of the BUPS to be delivered by the ARTECH company, four conveyor lines will be used to dehack, blend and package these brick. The bottom coarse conveyor line which the inspection station is located on will carry 1/8 of the total brick distribution. It is the distribution of the brick among the four conveyor lines that will set the cycle times that the conveyor line must have in order to meet the specified production rates.

The inspection system will inspect all the brick on the bottom coarse conveyor in the allotted dwell time, detect all cracks 2 mm or larger and deliver the results of good and bad brick locations to the BUPS. After the detection of a crack by the computer algorithm, that brick will be tagged as a "bad" brick, and the inspection system will tell the BUPS that the tagged brick is bad. When the BUPS is told by the inspection system that a brick is

"bad", the tagged brick will be left on the conveyor while the good brick are lifted and moved to another line. The bad bricks which are left on the conveyor line will be deposited into the waste conveyor. The "good" bricks that are transported to the next conveyor lines will be regrouped for packaging with brick from all deacking conveyor lines.

4.2 Global Requirements for Inspection Station

Global requirements such as the workspace and working environment have a significant impact on the design. Requirements and limitations such as environmental conditions, work space available and application requirements will define many of the characteristics of the system, so it is important to define them early.

4.2.1 Environmental Requirements

The environment that the inspection station will be designed to work within is the Corbin, Ky., GSB brick manufacturing facility. The environmental conditions for the manufacturing facility are as specified by Mr. Bob Keyes [14]. The ambient temperature will never exceed 110 degrees F, nor will it fall below 20 degrees F. The altitude of the Corbin, Ky., plant is listed at 977 feet above sea level. The relative humidity shall range from 15% to 90%. There shall be no chemical fumes that would have any effect on the inspection station. Airborne contaminates include normal dust and some sand (silicon carbide). The airborne contaminants should be minimal, but bearings, slides, etc. will be sealed due to uncertainty of this condition. Vibrations due to other machinery in the area will be minimal.

4.2.2 Layout of BUPS

The layout of the BUPS will include a gantry style transport system that will carry and distribute the bungs among the four dehacking conveyor lines. These four conveyor lines will perform the dehacking process, and the resulting rows of singulated brick will be transported to another set of conveyor lines. The second set of conveyor lines will regroup the brick for later packaging.

The inspection station will be integrated into the dehacking conveyor line which will carry the bottom two coarses of brick from the bungs. See Figure 1.1.2 for a sketch of the BUPS and the location of the inspection station with respect to the overall system. For further information concerning the design or layout of the BUPS, see Appendix B.

The inspection station will be located on the bottom coarse conveyor line which is 32 in. wide, and the inspection station will be located after the brick dehacking section of the BUPS but before the transfer area. The inspection station shall not exceed a length of 8 ft. or width of 8 ft. while operating in conjunction with the BUPS. See Figure 4.2.3.1 for a sketch of the workspace that the system must work within.

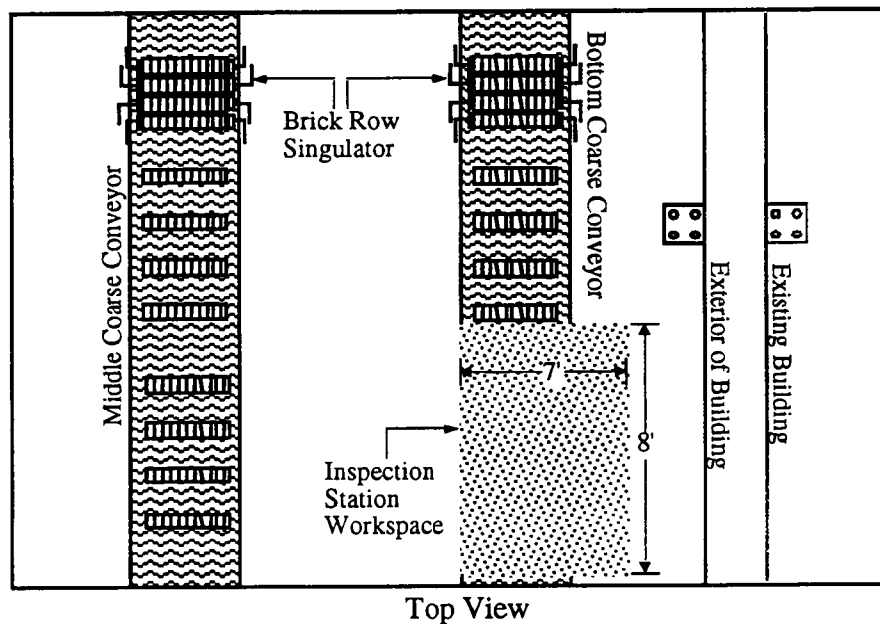


Figure 4.2.3.1.a Workspace for the Inspection Station

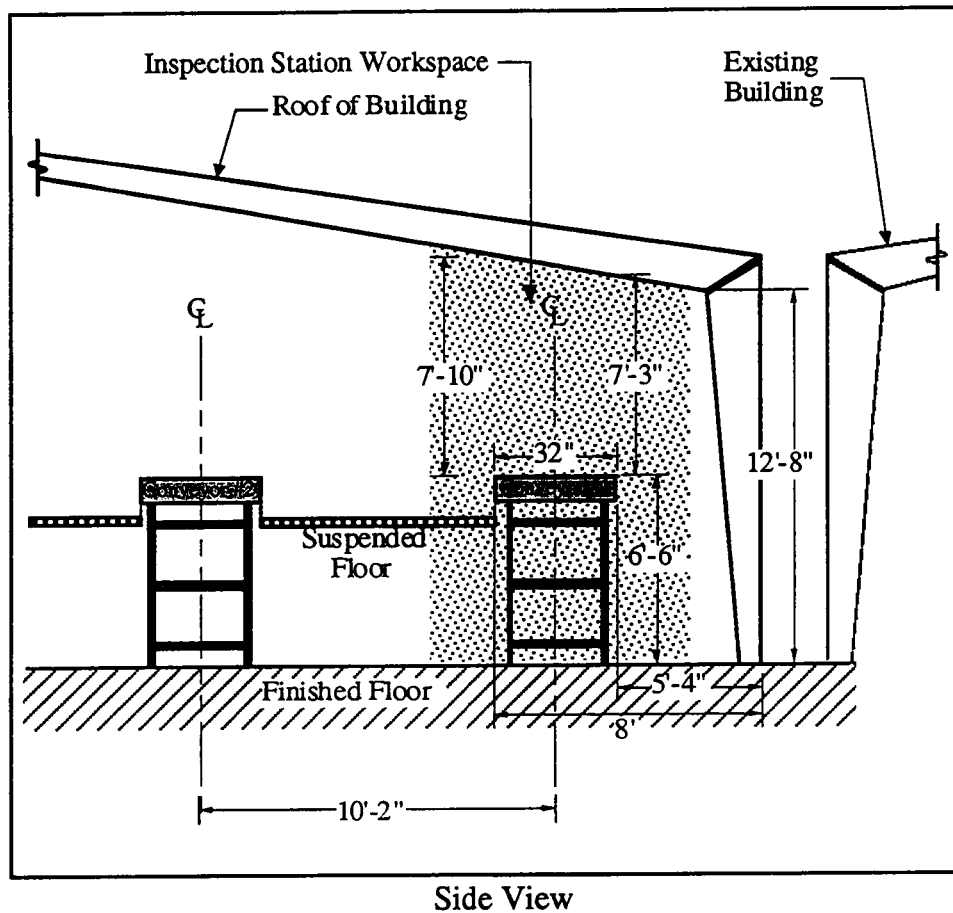


Figure 4.2.3.1.b Workspace for Inspection Station

4.2.4 Application Requirements

4.2.4.1 Types of Brick For Inspection

The inspection station will inspect a total of 18 different types of brick with different shapes, colors and textures. Of the various types of brick to be inspected, only five different sizes of brick will be inspected. Those sizes of brick include the standard size, modular size, queen size, king size and superking size. Therefore, the inspection system will need the flexibility to handle these different types of bricks. See Table 4.2.4.1.1 for an outline of the different brick types that the BUPs and inspection station will be expected to handle.

Table 4.2.4.1.1 Different Types of Brick at the Corbin, Ky., Plant

Type of Brick	Dimensions			Configuration of Brick for Inspection
	Bed (W)	Face (H)	Length (L)	
Standard Size (S/S) (95% of plant production)	3-1/2" x 2-1/4" x 8"			4 rows of 11 brick for a total of 44 brick
Modular Size (M/S)	3-1/2" x 2-1/4" x 7-5/8"			4 rows of 11 brick for a total of 44 brick
Queen Size (Q/S)	3" x 2-3/4" x 8"			4 rows of 9 brick for a total of 36 brick
King Size (K/S)	3" x 2-3/4" x 9-5/8"			3 rows of 9 brick for a total of 27 brick
Super King Size (SK/S)	4-5/8" x 2-3/4" x 9-5/8"			3 rows of 9 brick for a total of 27 brick

4.2.4.2 Presentation of Brick for Inspection

The brick will be presented for inspection at a ninety degree rotation off of the conveyor line with an elevation lift as well. In order for the brick set to be rotated and lifted into the inspection position, the dehacking equipment will clamp the rows of brick and rotate about a fixed pivot point that will give the necessary lift while performing the 90 degree rotation. The device that lifts and rotates the brick into the inspection position will be provided by ARTECH as a part of the BUPS. The lifter device designed by ARTECH that the inspection station must interact with is shown in Figure 4.2.4.2.1.

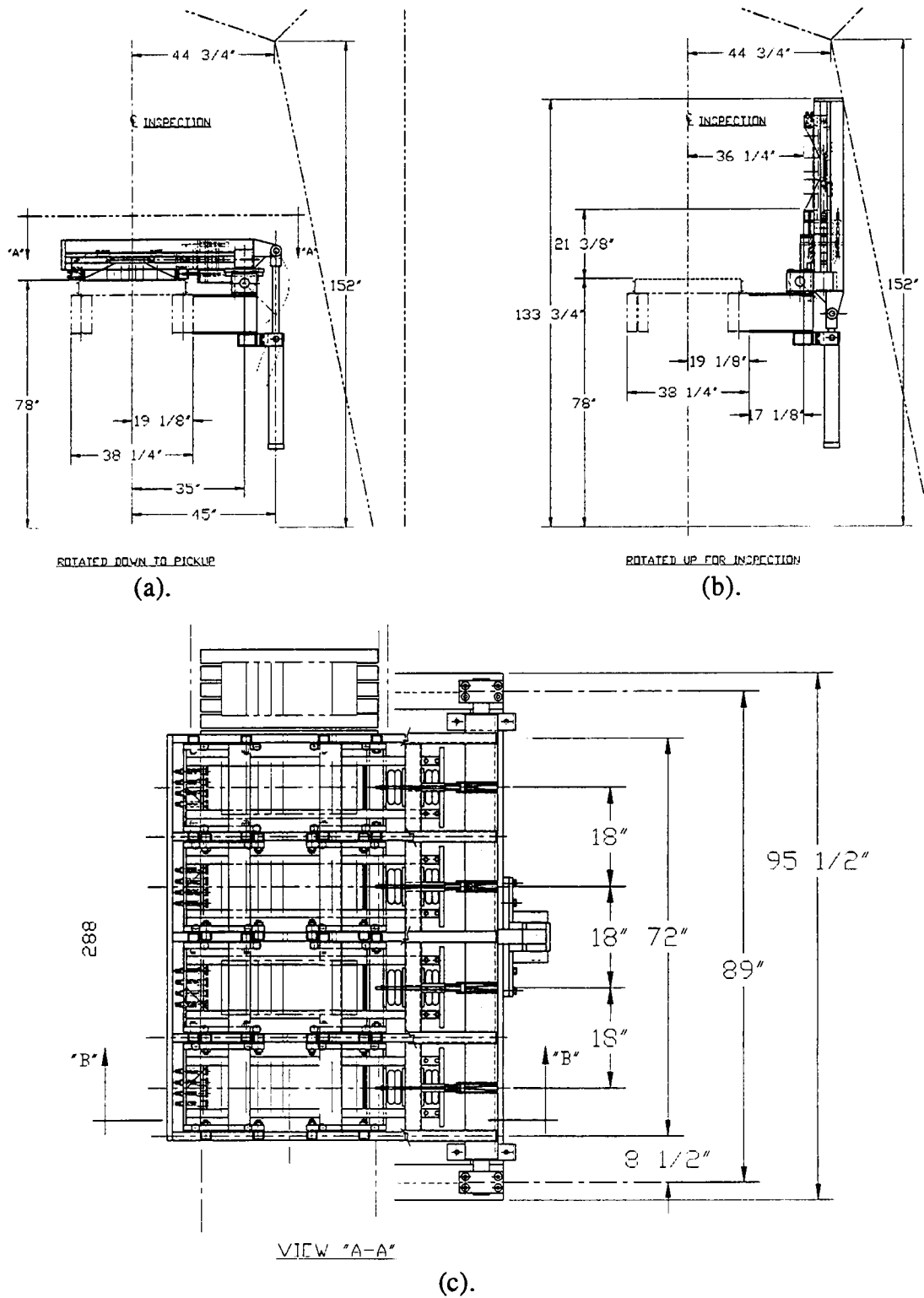


Figure 4.2.4.2.1 The Brick Positioner Device as Designed by ARTECH

The brick can be broken down into two major categories which include the S/S, M/S, Q/S, K/S and SK/S types of brick. The first of the two categories is the 8" brick which includes the S/S, M/S and Q/S brick, and the second of the two is the 10" brick which includes the K/S and SK/S brick. The 8" brick will be presented in the four row configuration while the 10" brick is presented in the three row configuration (see Figure 4.2.4.2.2 for the brick configurations as presented for inspection).

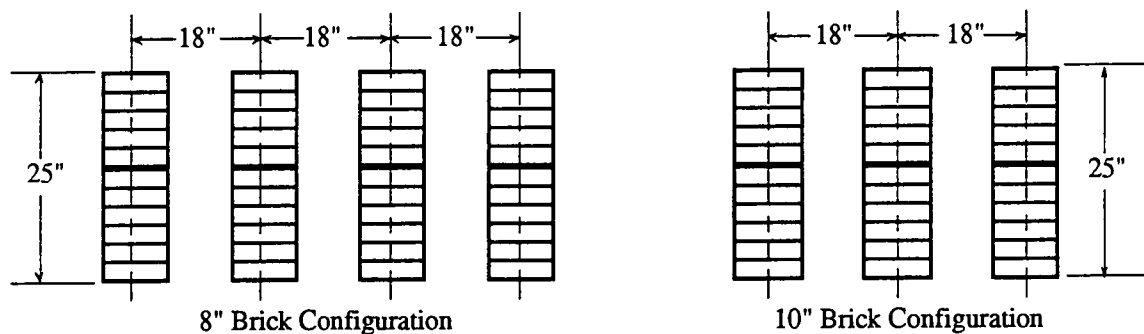


Figure 4.2.4.2.2 Brick Configurations as Presented for Inspection

4.2.4.2.1 Positional Accuracy of Brick Positioner

The positional accuracy for the presentation of the bricks for inspection shall be no worse than approximately $\pm 1"$ in the direction of motion for the conveyer belt and $\pm 0.5"$ in the direction perpendicular to the motion of the conveyer belt.

4.2.4.3 Motion Range

An adequate motion range shall be implemented that will provide for inspection of all brick configurations within a single sequence while also allowing for acceleration, deceleration, and constant velocity regions. The center to center distance between the rows of brick for the different configurations will be the same at 14 in., but the distance between the brick headers will vary depending on the brick.

In order to inspect the brick in the given configurations, the inspection station may utilize one, two or four scanners for completion of the inspection in the allowable dwell time. The number of scanners that are used will determine the necessary motion range and travel rates of the inspection system. See Figures 4.2.4.3.1, 4.2.4.3.2 and 4.2.4.3.3 for an outline of the motions for the one, two and four scanner alternatives.

4.2.4.4 Dwell Times

The inspection process will have to be completed in the allotted dwell time that allows for production rates to be met. This means that the inspection system must acquire images for all the brick in a given set within the given dwell time of 10 seconds. The total cycle time for the inspection line conveyor is 30.8 seconds with a total dwell time of 25 seconds. 5.8 seconds of the total cycle time is used for indexing the conveyor to the next position. The 25 second dwell time is for performing operations on the brick that allow for dehacking, inspection and transfer to the next conveyor line. See Table 4.2.4.4.1 for the distribution of the allotted 25 second dwell time.

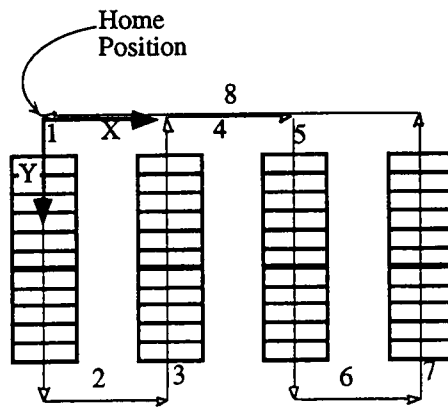
Table 4.2.4.4.1 Distribution of the Allotted Dwell Time

Type of Brick	Dwell Time for Inspection Process	Dwell Time to move Bricks into the Inspection Position	Total Dwell Time
All	10 seconds	15 seconds	25 seconds

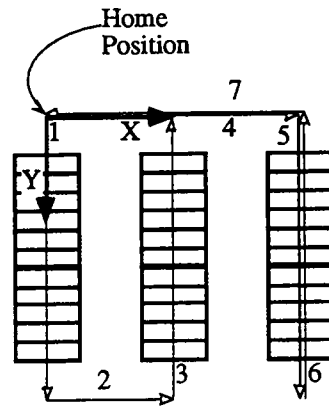
4.2.5 Electrical Requirements

4.2.5.1 Power Supply

The power supply for the inspection station shall not exceed 240 V.

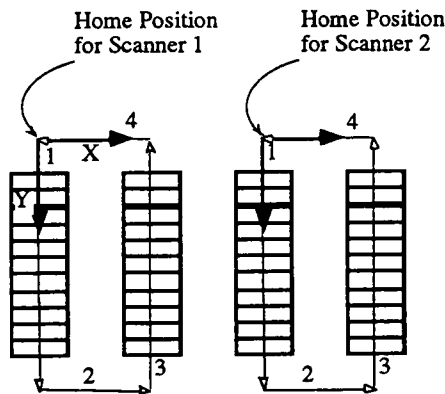


8" Brick Configuration

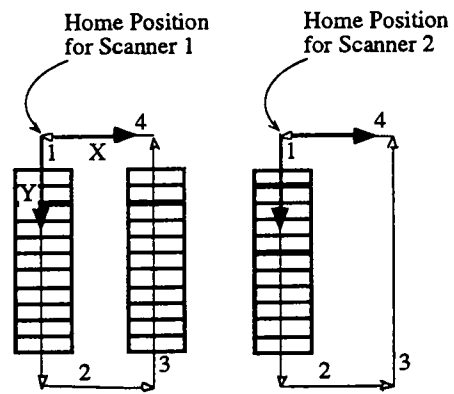


10" Brick Configuration

Figure 4.2.4.3.1 Motion Range and Sequence of Motion with One Scanner

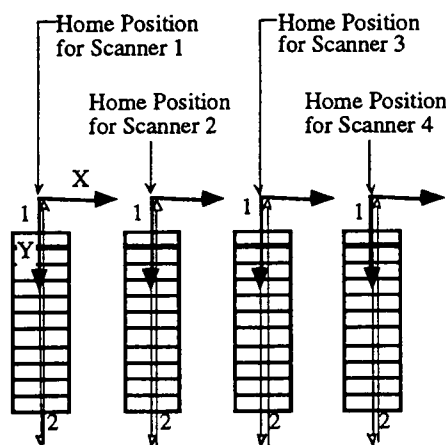


8" Brick Configuration

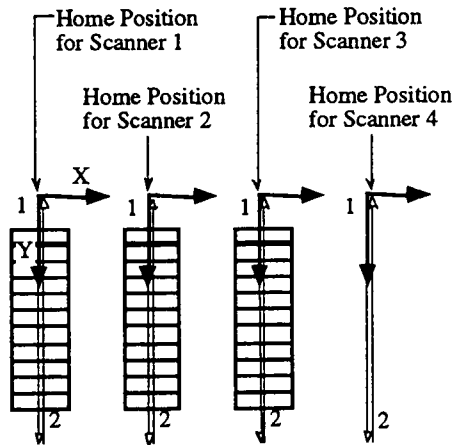


10" Brick Configuration

Figure 4.2.4.3.2 Motion Range and Sequence of Motion with Two Scanners



8" Brick Configuration



10" Brick Configuration

Figure 4.2.4.3.3 Motion Range and Sequence of Motion with Four Scanners

4.3 Control System & OCS Requirements

4.3.1 Functional and Performance Requirements

The control system and the OCS will be the central command center for all the subsystems of the inspection station. Both the image analysis and positioning systems have independent controllers to command operations for the successful completion of their respective tasks, but the control system will be responsible for issuing commands to both the image analysis and positioning system to ensure that everything works together properly. The control system shall be designed to include self-diagnostic algorithms to aid in the debugging and fault detection of the system. The control system and surrounding process modules required for the automatic inspection of brick are shown in Figure 4.3.1.1 in DFD (Data Flow Diagram) form [15]. Figure 4.3.1.1 shall be used as a software design requirement for the proper implementation of the control system.

The OCS will be the point of interaction between the inspection station and GSB associates, while the control system talks with the BUPPS and delivers commands to the optical inspection process and scanner positioning mechanism. The OCS will be equipped with a monitor and command input station that will allow for a GSB associate to monitor the inspection station (while in nominal or off-nominal modes) and issue commands to the inspection station as needed.

4.3.1.1 Nominal Operation

Nominal operating conditions are defined as normal operating conditions of the inspection system. When the inspection station is in nominal operation, high level commands will be delivered from the control system to the subsystems. The image analysis and scanner positioning subsystems will receive action commands that indicate when these subsystems should begin and end.

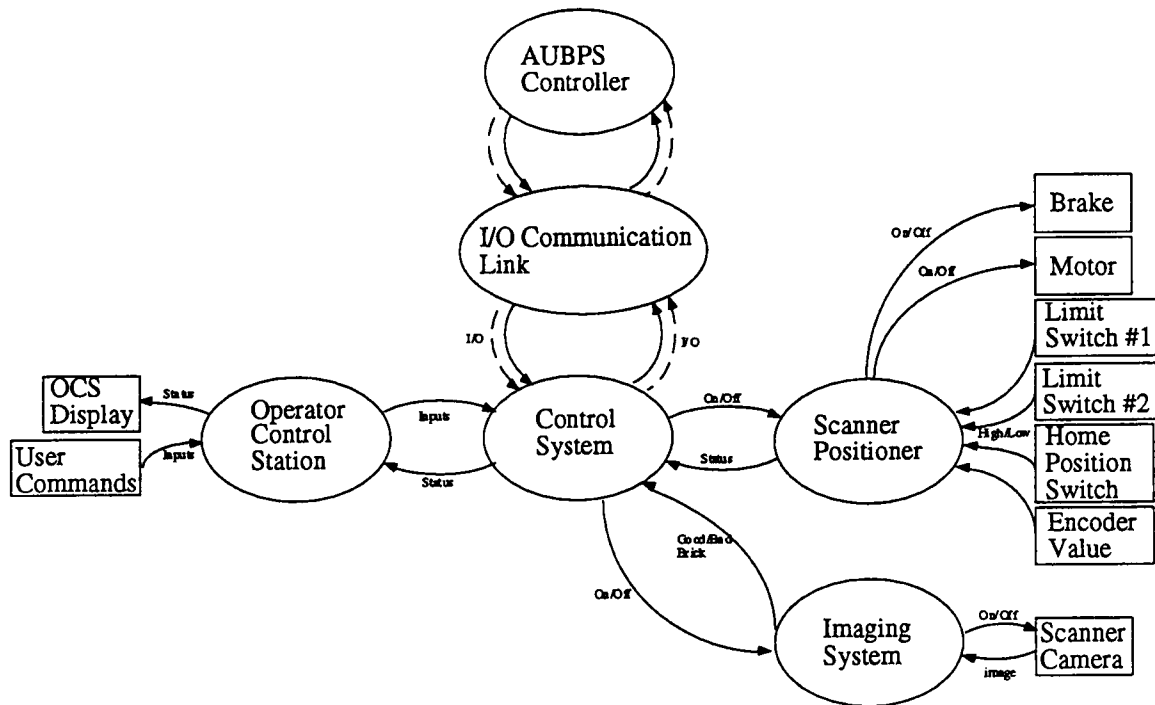


Figure 4.3.1.1 The Control System DFD

4.3.1.1.1 Integration of the Image Analysis Subsystem into the Inspection Station

The image analysis subsystem will receive commands from the control system to indicate when the inspection process is to begin and end. These communications will provide the image analysis subsystem with commands to start the image acquisition process and also when to stop the image acquisition process.

The results from the image analysis system will be given to the control station and the control system will then send the results to a shift register for the BUPs. As the results from the image analysis are received by the control system, the results will be relayed to the OCS monitor for display.

4.3.1.1.2 Integration of the Scanner Positioning Subsystem into the Inspection Station

The scanner positioning subsystem will receive commands from control system to indicate when the scanning maneuver should begin. Upon the acquisition of the command to begin the motion sequence, the positioning system will perform the series of motions that moves the scanner head over the brick.

When the positioning system has completed the scanning maneuver, the positioning system will communicate to the control system that the inspection of that set of brick has been completed. The control system will indicate to the BUPS that the inspection process has been completed, and the set of brick may be placed back onto the conveyor. The control system will send information to the OCS monitor to indicate the beginning and end of the inspection process, the status of the system's components including any fault conditions detected and the results from the inspection process.

4.3.1.1.3 Power On/Off Switch

The power switch for the inspection station will be located at the OCS.

4.3.1.1.4 Emergency Stop Switch

The emergency stop switch will be located at the OCS command panel, and activation of the emergency stop button will de-energize all actuators to stop the positioning system and activate the brakes to lock the positioning mechanism.

4.3.1.1.5 Restart Switch

The restart switch will be located at the OCS command panel and will be activated to restart the positioning system after an emergency stop or off-nominal condition. Upon activating the restart switch, the positioning system will return to the home position and the system will be ready to inspect the next set of brick.

4.3.1.1.6 Communication Link Switch

The inspection station will be equipped with a switch to activate or deactivate the communication link between the inspection station and the BUPS. This switch will only affect the output to the communication link, but the results of the image analysis will be preserved for process verification. This switch will be contained in the OCS either on the command panel or within the computer codes.

4.3.1.2 Off-Nominal Operation

Off-nominal operating conditions are defined as abnormal operating conditions such as system fault detection or initial system verification. When the inspection station is in the off-nominal operational mode, the control system will analyze the location of the fault and corresponding cause of failure. The results from the fault detection and corresponding failure mode will be relayed to the OCS for display on the monitor.

4.3.1.2.1 Fault Detection and Identification of Failure Mode

The subsystems of the inspection station will all have self-diagnostic codes that allow for the detection and identification of failure mode. If the failure occurs in a subsystem, the corresponding subsystem will relay the condition the control system, which in turn will shut-down the entire system and send a message to the OCS with the cause of the shut-down.

The control system will also be equipped with self-diagnostics that will enable the control system to detect failures that occur outside of the subsystems. As a minimum, the following diagnostic routines shall be provided:

1. Communication Link: Isolate communication component failure or verify operation.
2. Microprocessor Components: Verify that all processors are functional including peripheral devices with watch dog timer (A/D, D/A, serial ports, etc.)

3. Power Failure: Verify that all subsystems and control systems have not experienced power failure.

4.3.1.2.2 Placing the Inspection System Back in Nominal Operation

In order to place the inspection station back in nominal operation, the restart switch as described in Section 4.3.1.1.5 will be activated.

4.3.2 Physical Requirements

The control system and OCS will be contained in the dimensional envelope as described in Section 4.2.3, and the control station and OCS will also be equipped to be resistant to the environmental conditions as described in Section 4.2.1.

4.3.3 System Integration Requirements

In order for the inspection system to work properly with the BUPS, special considerations need to be given to the requirements for integration into the overall system.

The inspection station will serve the task of tagging the inspected brick as good or bad and communicating with the BUPS so that only the good brick are transported to the next conveyor line. The bad brick will be deposited in a waste conveyor. In order to communicate with the BUPS, the inspection system's controller will need to be linked with the controllers of the BUPS. The communication between the BUPS and the inspection station will provide information such as when the next set of bricks are ready to be inspected and what type of bricks are being inspected. The communication between the inspection station and the BUPS will provide information such as when the inspection process is completed so the bricks can be placed back on the conveyer line, which of the inspected bricks are bad, and their corresponding locations.

4.3.4.1 Communication with the BUPS by Relays

ARTECH will provide five relays that will be used as communication links between the dehacking system and the inspection system. The first and second relay will be energized when 8" brick are in production with the first relay representing the 4 rows by 11 configuration and the second relay representing the 4 rows by 9 configuration. The third relay will be energized when 10" brick are in production. The fourth relay will be energized when the dehacking system has positioned the bricks into the inspecting position and inspection can begin. All of the first four relays will be controlled by the BUPS, while the fifth will be controlled by the inspection system. The controller for the inspection station will energize the fifth relay when the inspection process is complete, the scanner device is moved out of the positioner path and the bricks can be set back on the conveyer. The first, second and third relays will be energized as long as that particular type of brick is in production, while the fourth and fifth relays will be momentary relays.

The inspection station will communicate with the BUPS through a series of approximately 50 relays which will allow for the results of the inspection, completion of the inspection process and system continue commands to be relayed to the BUPS controller.

4.3.4.2 The BUPS Controller

The BUPS will be controlled with an Allen-Bradley PLC model 540 with remote I/O peripherals. Therefore, all communication to and from the inspection station shall be organized in a compatible format.

4.3.4.3 Inspection System Output to the BUPS

The output of the inspection station shall provide 0 V to indicate a binary 0, and 24 V to indicate a binary 1 (See Table 4.3.4.3.1 for an outline of the tagging of the bricks). The output from the controller shall be sent through an I/O card that will translate the output to the proper voltages.

Table 4.3.4.3.1 Tagged Brick Indicator

Brick Tag	Good Brick	Bad Brick
Image Analysis Output	Binary 0	Binary 1
Input to the BUPS	0 Volts	24 Volts

4.3.4.3.1 Communication Link Switch

The inspection station will be equipped with a communication link switch that will enable the inspection station to turn on/off the communication link between the inspection system and the BUPS controller. This link will only affect the output from the inspection system as outlined above. Refer to Section 3.1.1.6 for information concerning the communication link switch.

4.4 Image Analysis Requirements

4.4.1 Functional Requirements

The image analysis system will scan the brick arrays utilizing one-dimensional scanners. The image data obtained by the scanners will be sent to a processor which will use the data to develop a two-dimensional image of the brick arrays. These images will be analyzed and processed to identify defects in the individual bricks. When defective brick are identified, the relay that corresponds to that particular brick will be activated.

4.4.1.1 Nominal Operation

When the system is running under normal conditions, the image analysis system will identify defective bricks in a series of steps. First, the line scanners will capture a series of one-dimensional images of the brick arrays. Second, the data which will form a two-dimensional image of the brick arrays will be relayed to the processor. Next, the brick array will be isolated from the image background, and the noise will be removed from the

entire image [2]. After this process is completed, each individual brick image will be isolated in the total array and processed for defect identification. After each brick array is processed, a signal specifying the location of the defective bricks in each array will be relayed to the control station and then to the BUPPS.

In order for the scanners to properly scan the bricks and obtain usable images, the scanners must receive a signal from the brick positioning system when the bricks are properly placed in the field of view of the scanners. The processor will send a signal to the control station so that the identification of the defective bricks can be monitored.

4.4.1.2 Off-Nominal Operation

When the system is not running under normal conditions, the image analysis will cease to scan the brick array and undergo a series of self-diagnostics. These diagnostics will include checking to see that power is still being supplied to the scanner and that the image processing algorithm is working properly. In addition, the positioning mechanism components such as motor controller will be checked to verify that it is in working condition.

4.4.2 Performance Requirements

To fulfill the necessary requirements of the manufacturing plant, the scanning system will obtain all the image data in the ten seconds allowed and send that data to the processor. The processor will analyze the brick images and detect defects in each brick and send that information to the rejection stage in the fifteen seconds allowed while the next set of brick are being positioned for inspection. In order to identify defects to 2 mm in width, a line scanner with a minimum of 512 pixels must be used.

In order for the image analysis system to operate effectively, the following performance requirements will be provided as a minimum.

4.4.2.1 Manually Variable Rejection Criteria Level

The inspection station's OCS shall be equipped with means of manually varying the tolerance level of the rejection criteria for the image analysis process. With increased tolerance, the image inspection system will search for smaller defects than 2 mm. With a decreased tolerance, the image inspection system will search only for cracks larger than 2 mm. The manually variable tolerance level will enable the system to be more or less critical in identifying defective brick.

4.4.2.2 Inspection Results Display

The results of the inspection process will be displayed on the OCS monitor. The bricks that are tagged as "bad" brick will be colored as red brick on the monitor while the "good" brick will be colored as green brick on the monitor.

4.4.2.3 Production Batch Quality Assurance

The inspection system will keep track of the number of "bad" bricks and total number of inspected brick. From this information, GSB will be able to monitor the quality of the brick that is in current production by the number of "bad" brick present in the lot. Production batch quality assurance will be performed in the OCS controller and made available to the user through the HMI (Human Machine Interface).

4.4.3 Physical Requirements

Due to OSHA regulations concerning lasers, an enclosure around the inspection station may be required to capture the "laser sheet" projected by the laser scanners. The enclosure could also be utilized to reduce the amount of airborne particles which may cause interference in the scanning process.

In order for the image analysis to be completed, the lens of the laser scanners must be approximately 5 to 8 inches from the brick when in the inspection position. The

distance from the lens of the scanner to the brick is flexible within reason as long as the distance is consistent throughout the scanning process.

4.4.4 System Integration Requirements

4.4.4.1 Controller Requirements

The image analysis subsystem will receive stop/start commands from the control system, and the control system for the image analysis will be responsible for running self-diagnostics for the imaging system.

4.4.4.2 OCS Functions

4.4.4.2.1 Power On/Off

The OCS will contain the power switch that turns the image analysis system on or off.

4.4.4.2.2 Emergency Shutdown Switch

The activation of the emergency shutdown switch will cause the image acquisition system to shutdown. The emergency shutdown switch will be located at the OCS.

4.4.4.2.3 Restart Switch

The OCS will contain the restart switch which will be used to restart the image acquisition and analysis system after an emergency stop or to place the system back in nominal operation after an off-nominal condition has been corrected.

4.4.4.2.4 Pause Switch

The OCS will be equipped with an pause switch that will allow for the image acquisition system to be temporarily stopped upon activation of the switch, and upon deactivation of the switch the image acquisition system will obtain images of the remaining brick.

4.5 Scanner Positioning Requirements

4.5.1 Functional Requirements

The basic function of the scanner positioning device is to provide a means of positioning the scanner head over a set of brick in such a manner that the entire set of brick can be inspected in the given dwell time.

4.5.1.1 Nominal Operation

For the case when the positioning system is operating under nominal conditions, the positioning system shall perform a series of motions that will move the optical scanner head over a set of brick within the allowed dwell time. Providing motion for the scanner head in such a manner that the mechanical device does not degrade the optical inspection process is essential.

In order for the motion device to transport the scanner head over the set of bricks, several events must take place with hardware and software interaction. Under nominal conditions, the inspection station and BUPS will be in contact through relays and communication links. First, the BUPS will energize a relay to specify the type of brick that is in production. Then, the BUPS will energize another relay to indicate that the set of brick is in the inspection position and that inspection of the brick may proceed. Once the motion controller has established the necessary accelerations and velocities, the motion device will transport the scanner head over the brick when the BUPS has energized the relay indicating that the brick is in the inspection position. The motion device will perform a series of moves that will transport the scanner head over every brick within a given set while maintaining position or velocity values when the scanner head is over the brick (See Figure 4.2.4.3.1, 4.2.4.3.2 and 4.2.4.3.3 for the sequence of motion for the scanning

process). For every motion within the motion sequence, the motion device will have to accelerate up to speed, travel at a constant speed and then decelerate back to zero velocity.

In order for the positioning system to perform its duty of moving the scanner head over the set of bricks properly, the positioning system must have a suitable control scheme, controller, sensors and motion device. The interaction of these subparts of the positioning system under nominal conditions is outlined in Figure 4.5.1.1.1.

4.5.1.1.1 Operational Modes

The inspection system shall be capable of operating in several different modes. Some of these different modes are listed below.

4.5.1.1.1.1 Constant Velocity

The inspection station will be equipped with an encoder and controller that will allow for constant velocity control. The encoder output will be used to provide velocity feedback which can be used in the servo-controller. The encoder value is integrated with respect to time in order to obtain a value for velocity feedback. When the scanner head passes over the brick headers for inspection, the velocity of the scanner head needs to be at constant velocity for reasons of inspection reliability.

4.5.1.1.1.2 Position

The inspection station will be equipped with an encoder and controller that will allow for position control. The encoder will provide position feedback which indicates the actual position of the scanner head.

4.5.1.1.1.3 Calibration

The inspection station will be capable of calibrating itself with computer codes and sensors. At the home position, the (X,Y) coordinates will be defined as (0,0).

4.5.1.2 Off-Nominal Operation

For the case when the motion device is under off-nominal operating conditions, the motion device has a different operational architecture. The motion system will enter the

off-nominal operational condition upon the detection of a problem or fault condition. The identification of the fault condition that initiates the off-nominal condition will be contained in the self-diagnostics portion of the flow diagram for nominal conditions (See Figure 4.5.1.1.1). Upon entering the off-nominal condition, the system will shutdown and provide information to the OCS to explain the purpose for the shutdown. The motion system will be provided with system failure identification codes that will aid the GSB associate in locating and correcting the failure. After the fault condition has been placed back in the nominal operational boundaries, the motion device can be placed back in the operational workspace from the OCS. After the motion device is within the operational workspace, the system can be restarted under nominal conditions. See Figure 4.5.1.2.1 for a flow diagram of the off-nominal operational condition.

4.5.1.2.1 Operational Requirements

4.5.1.2.1.2 Brakes

Automatic setting of brakes will occur during power failure or other non-standard conditions.

4.5.2 Performance Requirements

The performance of the motion device will be a major factor in the success of the inspection system. Therefore, the positioning system shall incorporate special design features to help ensure that the performance of the motion device can be optimized.

4.5.2.1 Nominal Operation

While operating under nominal conditions, the motion system shall have hardware and software that is capable of enhancing the performance of the positioning device. Some of these system enhancing methods are described in the following sections.

For Nominal Operation

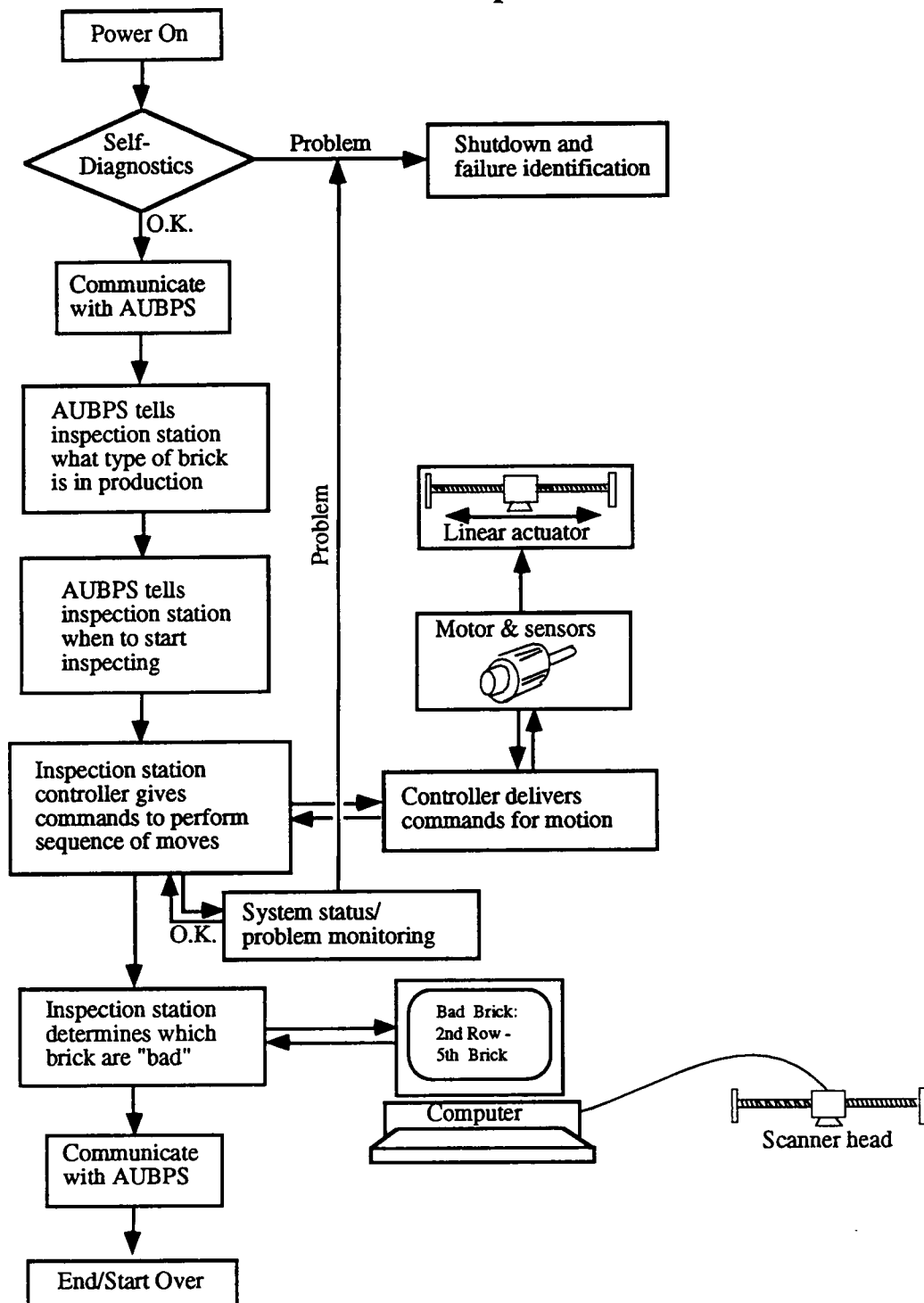


Figure 4.5.1.1.1 Nominal Operation Control Diagram for Positioning System

For Off-Nominal Operation

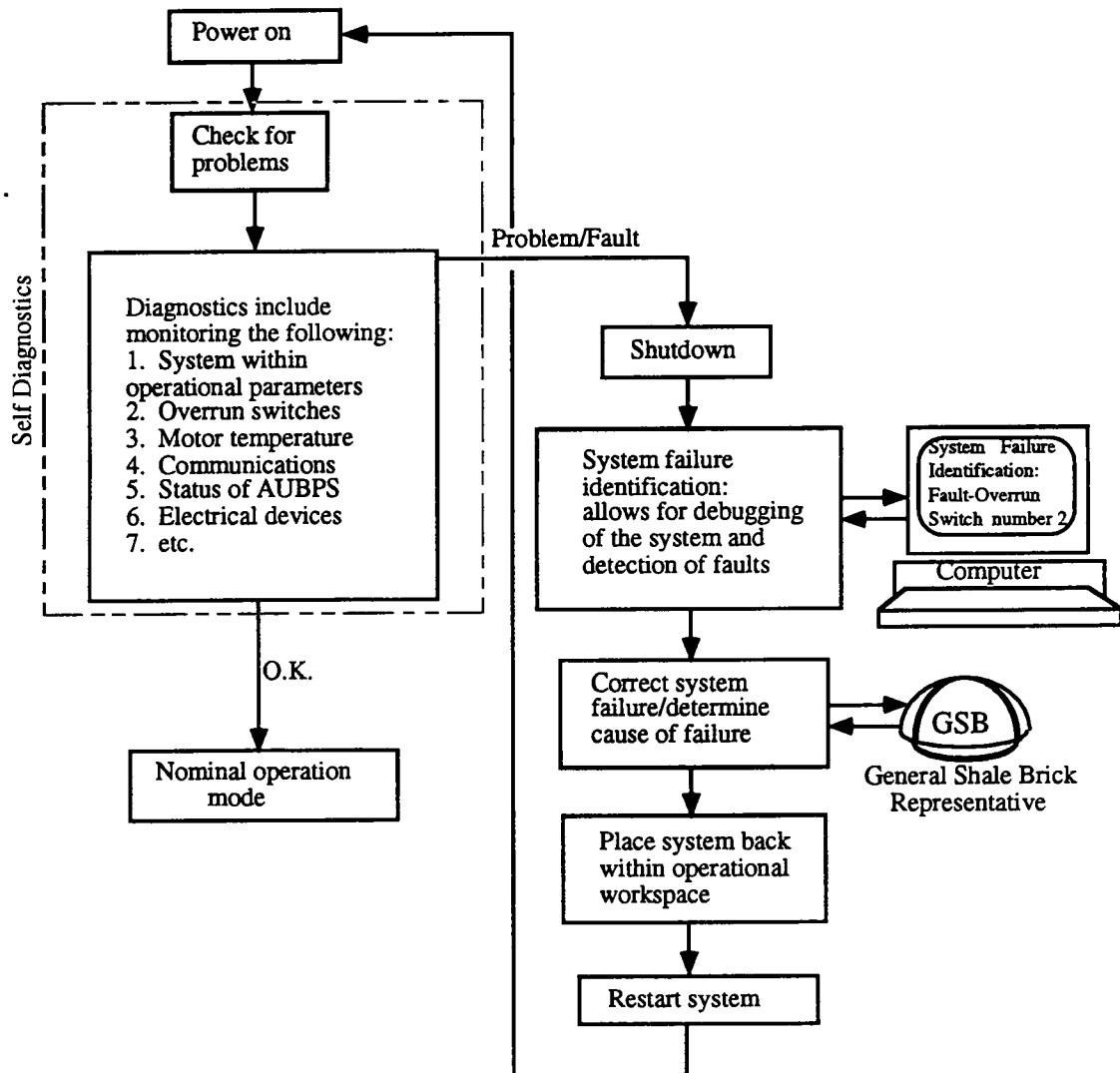


Figure 4.5.1.2.1 Off-Nominal Condition Diagram for Positioning System

4.5.2.1.1 Positioning System Optimization

The positioning system shall be designed with flexibility in the area of control schemes and velocity and acceleration profiles. The positioning device will be fine tuned in order to provide the best overall results for the optical inspection process.

4.5.2.1.1.1 Testing and Evaluation

The motion device will be tested and evaluated in order to optimize the performance of the positioning mechanism. The ability of the positioning device to accurately maneuver the scanner head at a constant velocity over the rows of brick with minimal vibrations and velocity errors will be the purpose of the evaluation and modification.

4.5.2.1.2 Failure Protection

The inspection system will be equipped with computer codes and hardware that will enable the system to protect itself from damage that might occur due to some type of failure. For example, overrun switches will be provided to prevent damage to the inspection station in the case where controller or motor should fail, causing the linear actuators to contact with the frame of the station. Upon detection of the linear actuators moving outside of the determined workspace, the system would automatically shut-down.

Special protection measures will also be provided for the electrical equipment. Fuses and optical isolators will be used to protect all electrical devices from electrical surges that would cause failure, and voltage and current regulation will minimize premature failure.

4.5.2.1.3 Condition Monitoring

The control system will automatically monitor the system condition to assure nominal operating conditions and protect the equipment. As a minimum, the following parameters will be monitored:

1. Motor Temperature: High temperature condition shall cause warning and then shutdown if condition persists.
2. Motor Current: Excessive current shall cause warning and then shutdown if condition persists.
3. Amplifier Temperature: High temperature shall cause shutdown.
4. System Voltage Levels: Each power supply shall be monitored for proper voltage levels, and shutdown will occur if voltage problem persists.
5. Amplifier Operational: Any circuit trips which are designed to protect the amplifier shall be monitored by the control system.
6. Communications: All communications will be monitored for proper operation. Repeated failures in communication links will cause the system to be disabled with an appropriate message given to the operator.
7. Status of the BUPS: The status of the dehooking line will be monitored.
8. Overrun Switches: Overrun switches will be incorporated and monitored to ensure that system does not leave the defined workspace, and if the system moves out of the defined workspace, the system will be disabled and the appropriate message will be given to the operator.
9. Encoder Value: The encoder will provide feedback for position control as well as position validation.

4.5.2.2 Off-Nominal Operation

The positioning system will be equipped with measures that aid in fault detection, fault identification, fault recovery and initial system verification. When the positioner is in the off-nominal operational mode, the failure identification function will allow the GSB associate locate, repair and restart the positioning system in the minimum amount of time. The system verification option will enable the inspection station to be properly integrated into the BUPS.

4.5.2.2.1 System Failure Identification

Upon failure of a mechanical or electrical module within the system, the control system shall be equipped with diagnostic routines which aid the operator in locating the failure. The diagnostic routines may be stored separately in computer files and called upon when needed. As a minimum, the following diagnostic routines shall be provided:

1. **Communication Link:** Isolate communication component failure or verify operation.
2. **Microprocessor Components:** Verify that both joint processors are functional including peripheral devices (A/D, D/A, serial ports, etc.)
3. **Amplifiers:** Verify that each amplifier responds properly to its drive input.

4.5.2.2.2 Initial System Verification

The inspection system will be equipped with computer codes and controls that will allow for the system to be verified upon delivery to the Corbin, Ky., plant. The system verification will include the verification of the smoothness of motion, absence of vibration, correctness of brick tagging and finally proper communication with the BUPS.

4.5.3 Physical Requirements

In this section, the physical restrictions, limitations and requirements are outlined.

4.5.3.1 Dimensional Requirements

The positioning system along with all the different components of the inspection station must fit within the dimensional envelope as outline in Figure 4.2.3.1 as well as be able to properly function with the brick positioner designed by ARTECH as shown in Figure 4.2.4.2.1.

4.5.3.2 Mechanical Requirements

4.5.3.2.1 Duty Cycle

For all types of brick that will be inspected, the total cycle time will be 30.8 seconds between indexing of the conveyor belt. The inspection station will have a dwell time of only 10 seconds to perform the inspection because the device to set the brick into the inspecting position will require the remaining dwell time. Therefore, the positioning system will be in operation $10/30.8 \times 100\% = 32.5\%$ of the time.

4.5.3.2.2 Life of the Positioning System

The positioning system will have a design life of 5 years and will be designed to meet all life travel requirements in accordance.

4.5.3.2.3 System Deflection

The inspection station should not have any vertical or horizontal deflection greater than 0.05" for worst case loading. The deflection limitation includes both static and dynamic loading conditions.

4.5.3.2.4 Reliability

The positioning system shall be capable of performing the scanning procedure with a reliability of at least 0.05" in both the horizontal and vertical directions.

4.5.3.2.5 Travel Rate

The speed that the inspection motion device will travel is dependent upon the allowable dwell time of the BUPS and the capabilities of the scanner device. Currently, the maximum allowable inspection time is 10 seconds for all types of brick.

The travel speed for the system will have a set maximum value of 1 m/s (3.28 ft/s), and the actual running speed can be any scaled down speed that will meet the necessary production rates.

4.5.3.2.6 Vibrations in the Inspection System

Vibration could significantly degrade the inspection process if allowed to become excessive. Therefore, vibrations within the inspection system must be minimized and the natural frequencies of the system avoided. Since the image analysis research is not yet

complete, no quantitative values have been set on the maximum vibrations allowable in the system. Therefore, the vibrations and deflections that take place throughout the system shall be minimized but limited by weight and cost considerations.

4.5.3.2.7 Allowable Stresses

4.5.3.2.7.1 Active Components (drive train)

Gears, bearings, and shafting shall be designed to supply the joint capabilities as specified in Section 4.2.4.3 while satisfying life and reliability requirements of Sections 4.5.3.2.2 and 4.5.3.2.4.

4.5.3.2.7.2 Inactive Components (load-carrying structures)

All load-carrying members shall be designed so that the stresses in the material based on maximum load capacity shall not exceed one-third of the minimum guaranteed value for the yield stress as specified by the manufacturer.

4.5.3.2.8 Motion Stops

Mechanical motion stops shall be provided for all joints. These stops shall restrain gearing and housing from undesired contact within the framework.

4.5.3.2.9 Brakes

Mechanical brakes will be provided that shall be capable of maintaining a locked position under maximum loading. The mechanical brakes will be engaged upon the detection of a system error, power failure or system shut-down. The brakes shall be fail-on such that the brakes are engaged in loss of power conditions.

4.5.4 System Integration Requirements

4.5.4.1 Controller Requirements

The control station that is comprised of all the controllers and hardware for the inspection station shall be organized in a neat and orderly fashion in such a manner as to

minimize the possibility of damage due to environmental conditions. The control station shall be maintained within the defined dimensional envelope unless otherwise stated.

4.5.4.2 OCS Functions

4.5.4.2.1 Power On/Off

The OCS will contain the power switch that turns the positioning system on or off.

4.5.4.2.2 Emergency Shutdown Switch

The ability for the inspection system to operate in a safe manner for the protection of employees is essential. A manual emergency stop button will be included on the OCS for manual shut-down of the system for any reason that the operator may deem necessary. Activation of the emergency stop switch will cause all motion devices to stop and will activate the brakes into the locking position.

4.5.4.2.3 Restart Switch

The OCS will contain the restart switch which will be used to restart the positioning system after an emergency stop or to place the system back in nominal operation after an off-nominal condition has been corrected. Upon restarting the system, the positioning system will return to the defined home position of the mechanism.

4.5.4.2.4 Pause Switch

The OCS will be equipped with an pause switch that will allow for the positioning system to be temporarily stopped upon activation of the switch, and upon deactivation of the switch the positioning system will continue to perform the uncompleted motion. The pause switch will allow for the positioning system to be stopped so that broken bricks can be moved off of the conveyor, and then continue.

4.5.4.2.5 Positioning System Monitoring

Positioning system monitoring shall be accomplished through the OCS where the status of the positioning system will be displayed. The status of the positioning system and the basic operational conditions shall be available to the user.

4.6 Material Requirements

4.6.1 General Materials

The inspection station, framework and all relative parts will be constructed with a grade of materials adequate for the specified application consistent with industry standards.

4.6.2 Metals

Metal parts shall be of a corrosion-resisting material or of a material with a corrosion-resistant treatment as specified in Section 3.3. Most of the metal to be used in the inspection station will be either aluminum or steel. If neither of these metals are available for a particular application, then different metal type can be considered.

4.6.3 Corrosion-Treatment

All parts subject to corrosion or in contact with dissimilar metals shall be given corrosion-resistant treatment such as plating, anodizing or painting.

The corrosion-resistant treatment shall be completely compatible with the material to be protected, the environment in which it is to be located and the use throughout its expected lifetime to which it will be subjected to wear, etc. The treatment shall follow all fabricating operations such as welding, drilling and tapping. All corrosion-resistant

treatment shall conform to applicable commercial standards and codes of the best quality grade. Painting shall include one coat of primer and two coats of lacquer or enamel.

4.7 Summary

As system design requirements are carefully developed, the design alternatives begin to surface and the feasible solutions becomes more apparent. As the system design requirements become more complete, more and more design options are eliminated, and eventually a defined boundary is placed around an acceptable range of alternative solutions. For instance, since the inspection process will be pure vertical motion, the use of some type of prismatic joint is preferable to a revolute joint. In order to accomplish the same task with even less accuracy, the revolute joint system would require two motors and path measurement systems, whereas with the prismatic joint, only one motor and path measurement system is required. The system design requirements that have been developed outline the performance, functionality and dimensional specifications for the inspection station, and these specifications will point a path toward the best possible design alternatives.

Chapter Five

The Conceptual Design

5.1 Overview

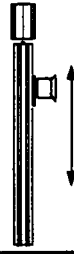
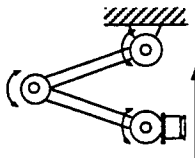
The conceptual phase of the design defines alternative design approaches, allows selection of a single approach and prepares the designer for the detailed design of the inspection station. The alternative design approaches are developed to give the consumer and engineer different options for the solution of the design. In Section 5.2, the basic design approach is selected, and then within that approach, three feasible solutions are presented with detailed discussion on each. Next, the preliminary design analysis is completed to give the designer insight for the loading conditions and performance characteristics for the alternative approaches. Then, the alternative designs are analyzed using trade-off analysis, and the most promising design is selected. Once the final design approach has been selected, more detailed analysis is performed to prepare the design for the detailed stage of the design process.

5.2 Alternative Design Approaches

The alternative design approaches for the positioning mechanism can now be developed within the boundaries as laid out in the system design requirements. The positioning device has some basic characteristics which define the approaches which are most feasible. Some of the basic characteristics worth note are that the system is a vertical application, approximate stroke length is 4 feet and time to complete the inspection process is 10 seconds. Within these boundaries and customer expectations, three basic design approaches emerge as possible solutions. The three approaches that the design of the positioning mechanism can follow are the use of a linear actuator, multiple revolute joints

or a crank shaft mechanism. These basic approaches are outlined in Table 5.2.1 with the corresponding advantages and disadvantages of each.

Table 5.2.1 Basic Design Alternatives for Positioning Mechanism

Design Approach	Principle	Advantages	Disadvantages
1. Linear Actuator	 Motion is purely vertical with one drive system per actuator.	- only one motor required to provide pure vertical motion - low cost - ease of control - high performance - good aesthetics	- less flexible than revolute joint approach - somewhat large space requirement
2. Multiple Revolute Joints	 Multiple revolute joints allows for vertical motion.	- highly flexible system	- multiple drive units required - high cost - more difficult to control - poor performance for pure vertical application
3. Crank Mechanism	 Revolute joint with vertical cam shaft provides pure vertical motion.	- only one motor required to provide pure vertical motion - proven technology - low cost	- difficult to control speed - poor aesthetics - high maintainance requirements

Of the three basic design approaches given in Table 5.2.1, the linear actuator approach has the most promise on the basis of the four major design considerations:

1. Performance: the linear actuator will give the maximum performance for the given application,
2. Cost: the linear actuator is among the most least expensive of the design alternatives,
3. Risk: the linear actuator is a proven technology with relatively low risk, and

4. Availability: the availability of the design solutions will depend greatly on the specific manufacturers availability.

With the linear actuator approach selected, some possible designs can be developed within the scope of this choice.

The three main linear actuator alternatives are briefly discussed in Table 5.2.2 and in greater detail later in this chapter. Since the customer has requested that no hydraulic actuators be used, electric actuators are the only applicable motion component available to the user. Various electric actuators, such as DC motors, stepper motors and linear motors, are all available as possible design options.

Table 5.2.2 Alternative Linear Actuator Design Approaches

Alternative Design Approach	System Outline
DC Servo Motor	The DC servo motor would be used in conjunction with a recirculating ball screw or belt drive, linear guideways and a position measurement system.
Stepper Motor	The stepper motor would operate with a recirculating ball screw or belt drive with linear guideways in an open-loop control system. External sensors would be used with the design.
Linear Motor	The linear motor would be a direct drive system that would function much like a stepper motor. The linear motor uses a closed-loop control architecture with a magnetic resolver which counts teeth as they mesh between the top side of the motor and linear guide.

Through consultation with General Shale and University of Tennessee Image Processing groups, it was decided that the four scanner approach would best suit the application. By using the four scanner approach, the time available to obtain each brick image is maximized and the system also becomes a one degree of freedom system, greatly

reducing its complexity. Therefore, the positioner shall be a 1 DoF motion device which provides motion only in the vertical direction with a camera carrying bar supporting four scanner modules. Linear guides will be provided on both sides of the positioner, and one or two-drive systems will be incorporated to provide motion, depending on future analysis.

Each of the design approaches would incorporate external sensors for position verification in case the motor should overrun the working space boundaries. Each system would also incorporate safety features such as brakes to hold the position of the device in a zero mechanical state. The possibility of one versus two-drive systems for each design approach is another consideration which will depend on the forces and moments generated by the positioner when in operation. The stepper motor approach will utilize either a recirculating ball screw or belt drive depending on the performance capabilities of each transmission for this application and cost considerations. The controller system for any of the above given design approaches would be either a VME bus environment, PLC environment or industrially hardened microcomputer package with peripherals.

For all designs, the positioner will communicate with the BUPS to determine when the brick are in the inspection position, when the inspection of the brick has been completed and the results of the inspection. The communication will be done by activation of approximately 44 to 50 on/off relays. The BUPS will set one of the switches to inform the inspection station to start inspecting. Upon completion of the inspection, the inspection station will set another switch to indicate completion and verify that the cameras are safely out of the workspace. The rest of the switches will be used for the indication of good or bad brick with either sinking or sourcing switches.

The basic conceptual design is shown in Figure 5.2.1 where any one of these design approaches could be implemented as a means of achieving the desired positioner mechanization. Any of the design approaches would be required to fit into this general form of functionality due to the system requirements outlined in the SDR.

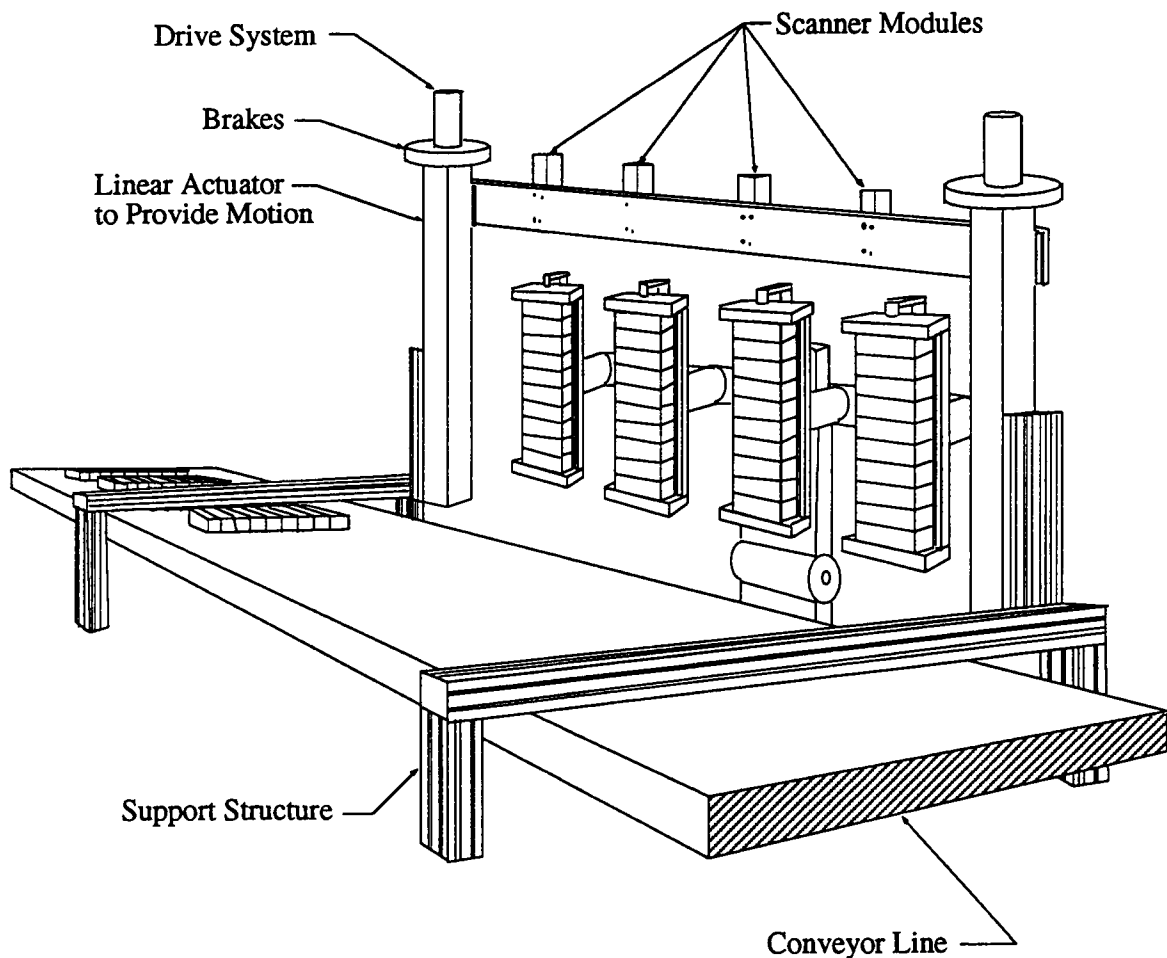


Figure 5.2.1 The General System Concept for the Camera Positioner

5.2.1 DC Servo Motor Design Alternative

The DC servo motor design approach is a technically sound and precise approach. Accuracy and performance are maximized with this design while cost is higher than some of the other possible design approaches. The DC motor design approach would be comprised of linear actuators that would either be belt or ballscrew driven with fail safe brakes, encoder path measurement system, and a brush or brushless DC servo motor.

The DC motor will operate with the aid of a path measurement system such as an incremental optical shaft encoder. The path measurement system will be used to control the velocity and position of the positioner device using a closed-loop feedback control architecture. External proximity sensors will be used as overrun switches in the case where the motors position the slider mechanism outside of the defined workspace. The incorporation of the overrun switches is to minimize the possibility of the positioning system damaging itself. The closed-loop servo-control system will be contained in the electronic controller which will be interfaced to the BUPs, image analysis system and OCS. The system will be computer controlled and the user will operate the inspection station and positioning device through the OCS. The overall system control architecture for this approach would be either an industrially hardened PC environment or a VME bus environment. The motion control would be accomplished using a commercial controller/amplifier.

The DC motor will provide motion for the scanners to obtain 1-D images of the brick with the laser scanners. The DC motor will be connected to a recirculating ball screw or belt drive system in order to generate linear motion for the scanners from the rotational motion generated by the DC motor. The DC motor would require a braking mechanism to maintain the vertical position of the cameras while stationary between inspections and also to maintain the cameras in a zero mechanical state.

The positioner may have one or two-drive systems based on results of analysis on stress loads, bending moments, deflection and fatigue of the transmission, slider and camera carrying bar. Using one-drive system (including motor, path measurement, axis controller, sensors, etc.) instead of two would reduce the cost and complexity of the system if feasible. If two-drive systems are necessary, a leader and follower approach could be taken in the control of the positioner as the two-drive systems would operate in

tandem. The two-drive system has the advantage of adding structural rigidity and design flexibility to the system.

5.2.2 Stepper Design Alternative

The stepper motor design alternative is similar to the DC motor approach with the exception that the motion of the stepper motor is controlled by an open-loop controller. The open-loop controller operates by sending pulses to the motor and assuming that the motor will move a distance that corresponds to the number of pulses sent. In order to minimize errors, the motor can be homed using an external sensor to set a zero or start point from which the pulses can be counted. In addition, overrun switches can be implemented so that the occurrence of skipped steps would not cause the system to move outside of its defined workspace. Every time the positioner scans a pallet of brick and returns to the rest position at the top of the inspection station, the motor will home its position by making contact with the home positioner switch. The overall system controller for the stepper motor design could incorporate either the PLC environment with motion control modules or an industrially hardened microcontroller package with motion control peripherals. Like the DC motor alternative, commercial drive controllers are available for superior motion control.

The stepper motor has the unique attribute of having a holding torque while stationary. If the holding torque of the motor is large enough, the holding torque could be used to maintain the vertical position of the cameras throughout the dwell time of the positioner without the need for a parking brake. A fail-safe brake would still be required to maintain the vertical position of the cameras under loss of power or emergency shut down conditions. Similarly to the DC motor alternative, linear guides would be used to support the system and ensure linear motion. Either a recirculating ball screw or belt drive would be used for the transmission of the positioner depending on further analysis. Again, the

positioner would have either one or two-drive systems depending on further analysis. The stepper motor approach would be essentially the same as the DC motor approach shown in Figure 5.1.1.1 except for the stepper motor being the drive system with no path measurement system.

5.2.3 The Linear Motor Design Approach

The linear motor approach would also fit inside the basic design structure as shown in the DC motor approach (Figure 5.1.1.1), but the motor and linear guides together would be one mechanism. The linear guide would function not only as the linear support of the actuator but also serve as the drive mechanism all in one package. The linear motor can incorporate electric braking modules to aid in maintaining the vertical position of the camera carrying bar. The linear motor comes with a special control module which could easily fit in a PLC, VME or microcomputer environment. The linear motor approach would utilize either two parallel linear motors or one linear motor in parallel with a linear guide mechanism.

5.3 Preliminary Design Analysis of Alternatives

The preliminary design analysis of the alternative design approaches can be broken down into sections which build on themselves until the preliminary analysis is complete. To begin, the four scanner alternative approach was selected by General Shale together with the University of Tennessee to maximize the flexibility of the system. From this design selection, the weight of the scanner modules and the carry bar can be determined for the material selected. The scanner carrying bar with the scanner modules as conceptualized for the application is shown in Figure 5.3.1. Each of the scanner modules will contain a laser and rotating mirror with drive motor which will be assembled into the scanner

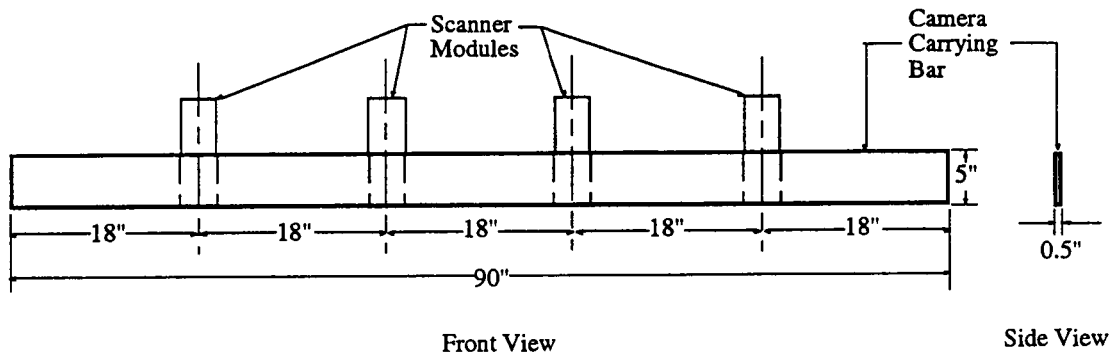
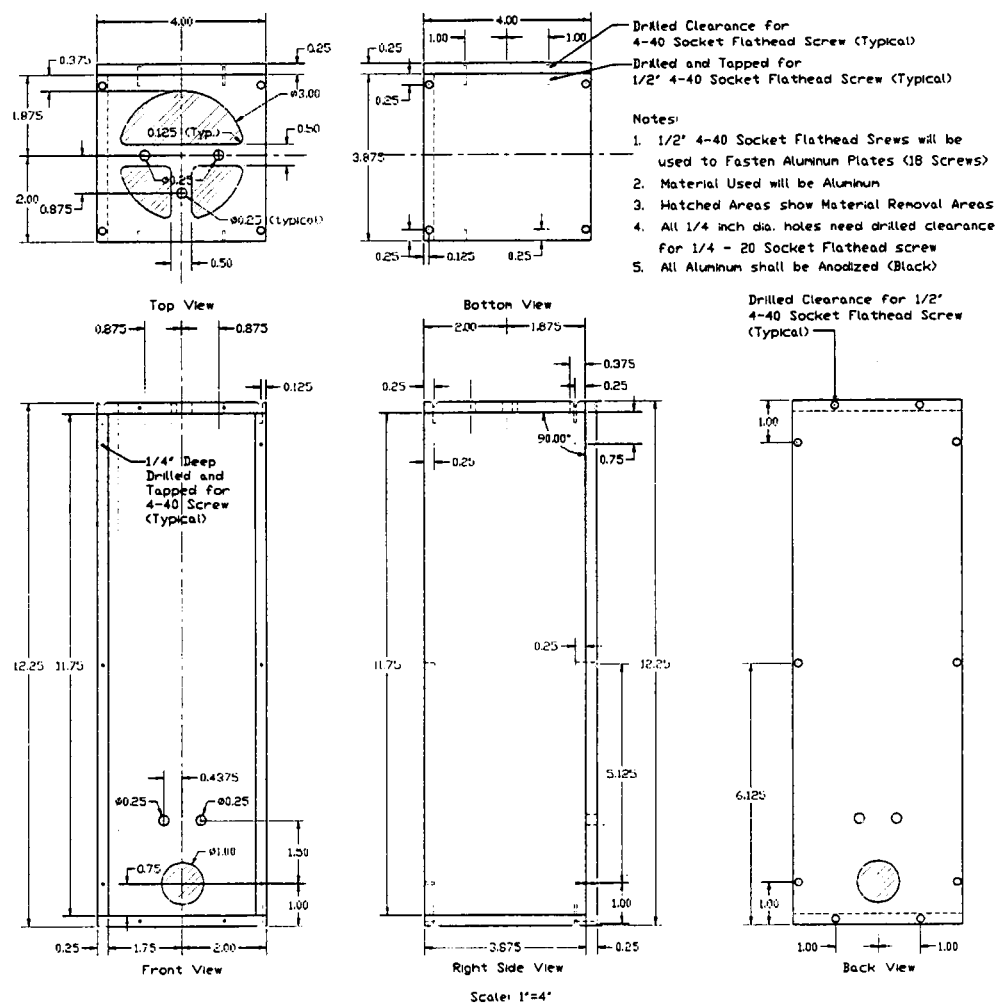


Figure 5.3.1 The Camera Carrying Bar with Scanner Modules



Enclosure for Laser Scanner Equipment

Designer:
Units for Drawing:
Date:

Jeffrey W. Buck
Inches
August 25, 1995



Figure 5.3.2 The Laser Scanner Equipment Enclosure

equipment enclosure as developed in Figure 5.3.2. The scanner and rotating mirror operate by spreading a laser light around to form a laser "sheet" which gives a 1-D image of the brick. A 2-D and 3-D schematic of the laser scanner are given in Figure 5.3.3.

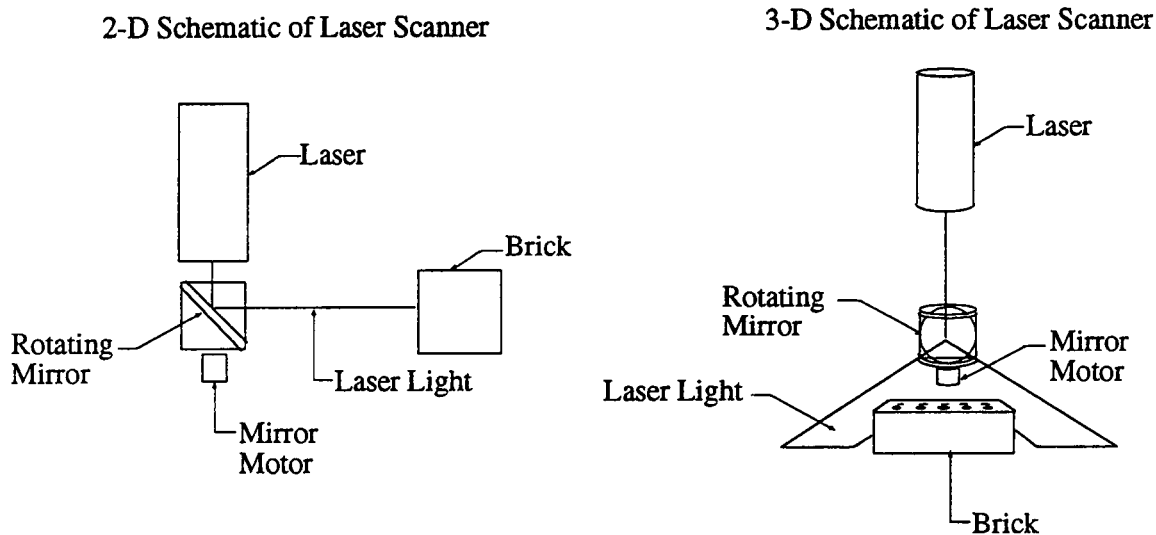


Figure 5.3.3 2-D and 3-D Schematic of 1-D Laser Scanner

The laser scanner is an AccuRange line scanner by Acuity Research with a MicroMo motor which powers the rotating mirror. The maximum motor speed is 5900 RPM which would correlate to a maximum of 196 scans per inspection cycle where each revolution of the motor corresponds to a single scan of laser scanner. The scanner has a variable motor speed, but the 192 scans per inspection cycle is the upper bound for total number of scans in an inspection cycle while operating the positioner at a speed of 12.5 in/sec as calculated in Section 5.3.1. The total width of the brick row to be inspected is approximately 25 inches which indicates that the scanner will scan the brick for approximately 2 seconds. A more typical operating speed of the laser scanner motor might be 2600 RPM which correlates to 88 scans per inspection cycle while the positioner travels at 12.5 in/sec. The positioner will have the flexibility to adjust the speed of the positioner somewhat so that there would be more or less scan time. If the positioner speed is reduced

such that there is a 5 seconds scan time, the laser scanner would acquire 216 scans per inspection cycle. The impact of raising the scan time to 5 seconds is that the positioner must then accelerate, decelerate and then return to the home position of the positioner in the remaining 5 seconds. This would take up the entire 10 second dwell time with no spare time remaining but would allow for more scans to be acquired if necessary.

The scanner modules are made of aluminum and have a total weight of 6 pounds each, including the enclosure as shown in Figure 5.3.2 as well as the laser and mirror with the motor drive. The weight of the carry bar is determined by multiplying the volume of the carry bar and density of the material. For aluminum, the density (ρ) is 0.10 lb/in³ [16], and for steel, ρ is 0.28 lb/in³ [16]. Since there are four scanner modules which each weigh 6 pounds, the total weight of the camera carrying bar with the scanner modules can be calculated by the formula:

$$W_{\text{total}} = W_{\text{carry bar}} + 4 * W_{\text{scanner module}} \quad (5.1)$$

where for an aluminum carry bar, $W_{\text{total}} = 46.5$ pounds, and for a steel carry bar, $W_{\text{total}} = 87$ pounds.

The load distribution for the carriage bar is important since it will determine the stress and deflections that the bar must endure. In Figure 5.3.4, the load distribution for the carriage bar is shown. The actual load distribution for the carriage bar is a distributed load across the entire beam due to the weight of the beam, and small additional loads which represent the scanner modules which are carried by the beam also. The load distribution has been approximated to a distributed load across the length of the beam which includes the weight of the beam and the weight of the scanner modules.

The stroke that is required to operate around the brick lifter device as provided by ARTECH is approximately 47 inches. The stroke length includes 25 inches to inspect the brick array, 5 inches to stop after inspecting on the downward motion, 12 inches on top of

the brick array in order to leave the lifters workspace and 5 inches as the width of the carriage bar. These lengths added up give the 47 inch stroke length.

Next, the position, velocity and acceleration motion profiles are developed in accordance with the system design requirements. From the velocity and acceleration profiles, both static and dynamic loading can be evaluated by considering the effects of eccentric loading, acceleration and cyclic motion. This analysis will determine the merits of the one-drive system versus the two-drive system.

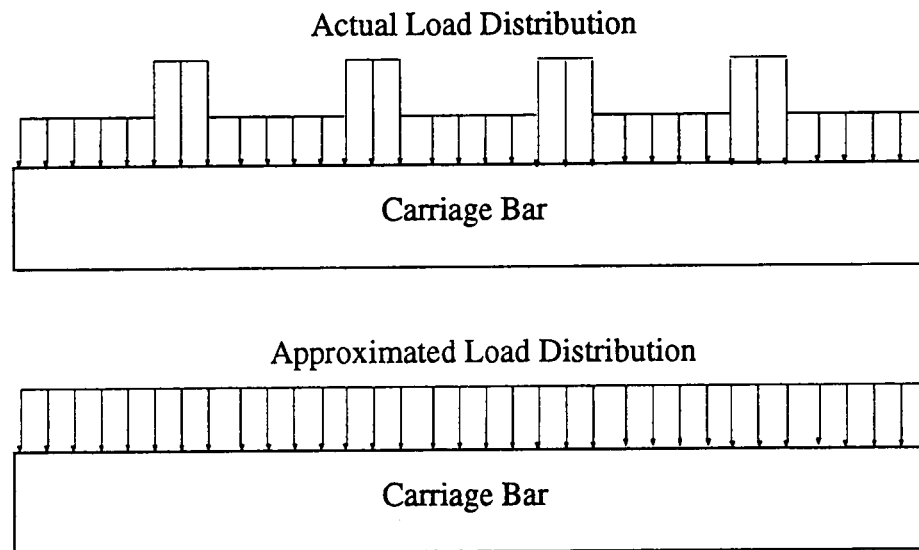


Figure 5.3.4 Scanner Bar Load Distribution

5.3.1 Motion Profile

The design requirements specify that the inspection station should have a total of 10 seconds to complete the inspection of each set of brick. Within this time frame, the positioner will require 4 seconds to move down for image acquisition and another 4 seconds to return to the home position. The drive system will follow the velocity profile as shown in Figure 5.3.1.1 which includes acceleration, constant velocity and deceleration regimes.

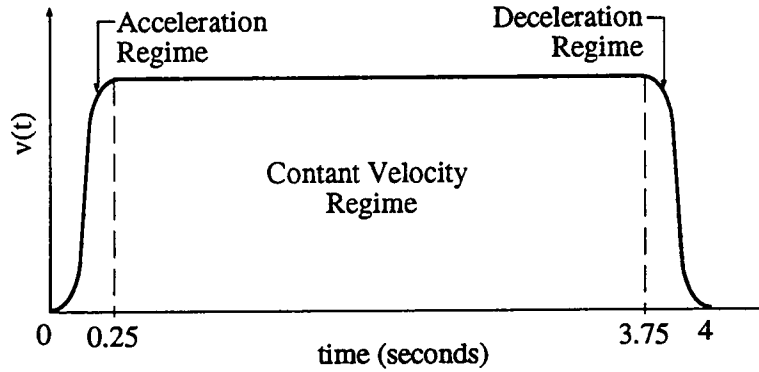


Figure 5.3.1.1 General Velocity Profile

In order to achieve smooth motion through the position, velocity and acceleration profiles, a third order polynomial is used to describe the velocity as follows:

$$v(t) = a_3t^3 + a_2t^2 + a_1t + a_0. \quad (5.2)$$

From Equation (5.2), we can relate the position, acceleration and jerk of the positioner by:

$$s(t) = \int v(t) dt = \frac{a_3t^4}{4} + \frac{a_2t^3}{3} + \frac{a_1t^2}{2} + a_0t + C, \quad (5.3)$$

$$a(t) = 3a_3t^2 + 2a_2t + a_1, \text{ and} \quad (5.4)$$

$$j(t) = \frac{da(t)}{dt} = 6a_3t + 2a_2. \quad (5.5)$$

By setting up the velocity profile such that the minimum amount of time that is available to accelerate the cameras is 0.25 seconds and to decelerate the cameras is 0.25 seconds, the velocity profile is established as shown in Figure 5.3.1.1. The acceleration term should be maximized to allow so that the designer can design the system under worst load condition.

Evaluation of the velocity equation for the acceleration regime where $t_0 = 0$ seconds, $t_f = 0.25$ seconds, $v(t_0) = 0$, $v(t_f) = \text{slew velocity}$, $a(t_0) = 0$ and $a(t_f) = 0$ yields the following results as calculated in Appendix B.

$$v(t) = -1604.3t^3 + 601.6t^2 \quad (\text{in/sec}) \quad 0 < t < 0.25 \text{ seconds} \quad (5.6)$$

$$a(t) = -4812.8t^2 + 1203.2t \quad (\text{in/sec}^2) \quad 0 < t < 0.25 \text{ seconds} \quad (5.7)$$

$$s(t) = -401.067t^4 + 200.433t^3 \quad (\text{in}) \quad 0 < t < 0.25 \text{ seconds} \quad (5.8)$$

$$j(t) = -9625.6t + 1203.2 \quad (\text{in/sec}^3) \quad 0 < t < 0.25 \text{ seconds} \quad (5.9)$$

The slow velocity at time 0.25 seconds is $v_{\text{slew}} = 12.53 \text{ in/sec}$, which leads to the next set of profile equations for the constant velocity regime where $t_0 = 0.25 \text{ seconds}$, $t_f = 3.75 \text{ seconds}$, $v(t_0) = \text{slew velocity} = 12.53 \text{ in/sec}$, $v(t_f) = \text{slew velocity} = 12.53 \text{ in/sec}$, $a(t_0) = 0$ and $a(t_f) = 0$.

$$v(t) = 12.53 \quad (\text{in/sec}) \quad 0.25 < t < 3.75 \text{ seconds} \quad (5.10)$$

$$a(t) = 0 \quad (\text{in/sec}^2) \quad 0.25 < t < 3.75 \text{ seconds} \quad (5.11)$$

$$s(t) = 12.53(t-t_0) + 1.565 \quad (\text{in}) \quad 0.25 < t < 3.75 \text{ seconds} \quad (5.12)$$

$$j(t) = 0 \quad (\text{in/sec}^3) \quad 0.25 < t < 3.75 \text{ seconds} \quad (5.13)$$

For the final portion of the profile, the deceleration regime, the evaluation of the profile equations can be found using the same method as in the acceleration regime, but now $t_0 = 3.75 \text{ seconds}$, $t_f = 4 \text{ seconds}$, $v(t_0) = \text{slew velocity} = 12.53 \text{ in/sec}$, $v(t_f) = 0$, $a(t_0) = 0$ and $a(t_f) = 0$.

$$v(t) = -1603.84t^3 - 18644.64t^2 + 72172.8t - 93022.72 \quad (\text{in/sec}) \quad 3.75 < t < 4 \text{ seconds} \quad (5.14)$$

$$a(t) = 4811.52t^2 - 37289.28t + 72172.8 \quad (\text{in/sec}^2) \quad 3.75 < t < 4 \text{ seconds} \quad (5.15)$$

$$s(t) = 400.96(t^4 - t_0^4) - 6214.88(t^3 - t_0^3) + 36086.4(t^2 - t_0^2) - 93022.72(t - t_0) + 45.42 \quad (\text{in}) \quad 3.75 < t < 4 \text{ seconds} \quad (5.16)$$

$$j(t) = 9623.04t - 37289.28 \quad (\text{in/sec}^3) \quad 3.75 < t < 4 \text{ seconds} \quad (5.17)$$

Using these equations in the Excel spreadsheet application, the velocity, position, acceleration and jerk profiles are plotted as shown in Figure 5.3.1.2. From the results obtained with the spreadsheet, the maximum acceleration term is 72.2 in/sec², where acceleration downward is positive and acceleration upward is negative. For a downward move, the positioner would accelerate downward, then travel at a constant speed and then accelerate upward (or decelerate).

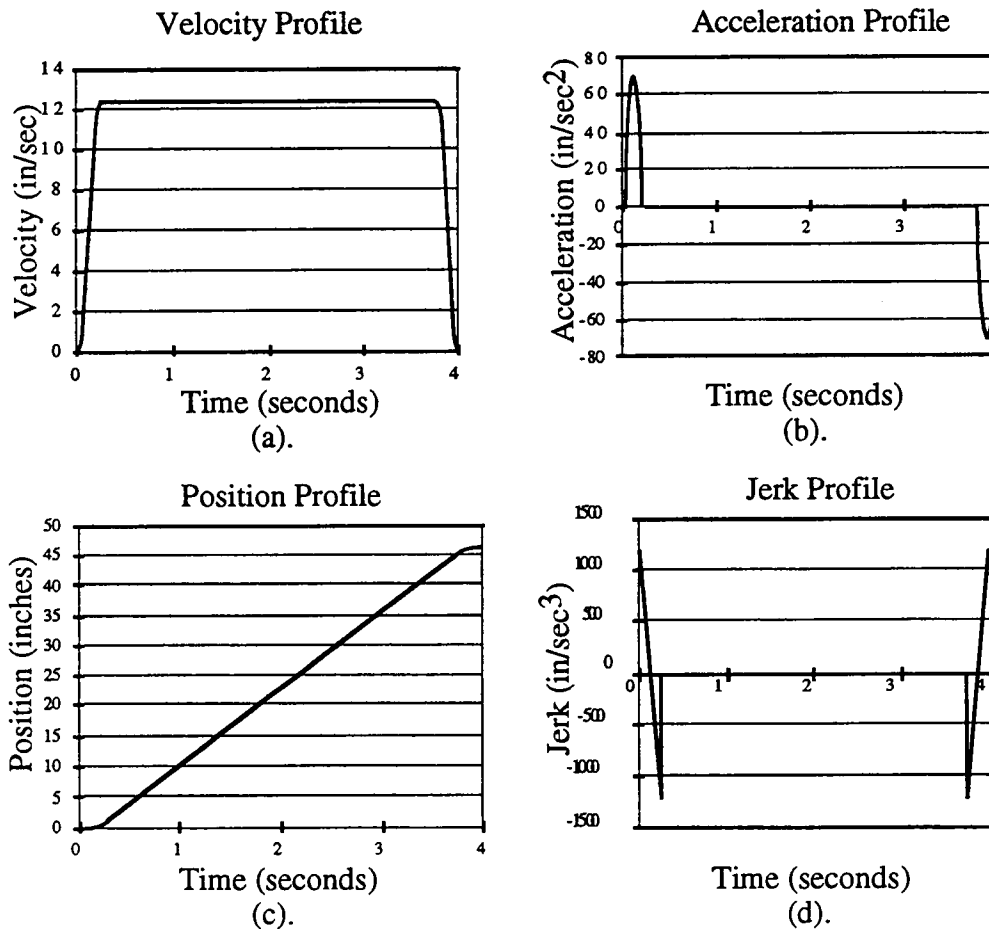


Figure 5.3.1.2 (a,b,c &d) Velocity, Acceleration, Position and Jerk Profiles

5.3.2 Static and Dynamic Loading

Now that the motion profile for the positioner has been established for the maximum acceleration condition, the loading conditions for the positioner can be calculated. The free body diagrams for the one-drive system and two-drive system are shown in Figure 5.3.2.1, as well as the forces and moments that are acting on the system for the respective drive systems.

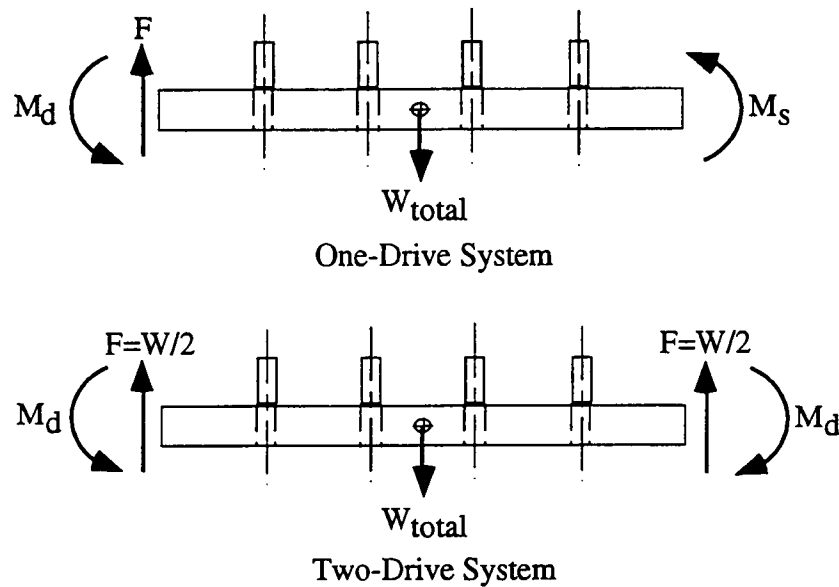


Figure 5.3.2.1 Free Body Diagrams for One and Two-drive System

5.3.2.1 One-Drive System

The moments which are included with the one-drive system can be calculated using the moments described in Figure 5.3.2.1.1. The analysis of the one-and two-drive systems uses the assumption that the physical representation of the actual system can be modeled by approximation as simple beams under loading conditions similar to the actual system. The end conditions for the one-drive system is fixed at one end and free but guided at the other end. The loading of the beam has been approximated as a uniformly

distributed load as shown in Figure 5.3.2.1.1. The stress and load distribution is developed from the fundamental assumption that the linear guides will maintain a zero degree departure angle of the beam leaving the linear guide. With a force on one end maintaining the vertical position and the moments on both ends induced by the linear guides, the distribution shown in Figure 5.3.2.1.1 is created for a uniformly distributed load. This model is analogous to actual system where the beam is fixed at one end and free but guided at the other end.

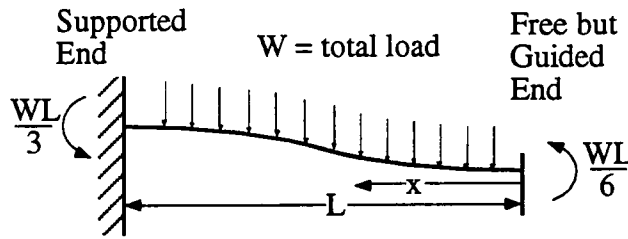


Figure 5.3.2.1.1 Forces and Moments for the One-drive System [17]

The stress at any point on the beam can be found with the expression [17]

$$S = \frac{Wl}{Z} \left[\frac{1}{3} - \frac{x}{L} + \frac{1}{2} \left(\frac{x}{L} \right)^2 \right]. \quad (5.18)$$

The deflection (y) of the beam in Figure 5.3.2.2 at any point along the beam can be found using the following equation [17]:

$$y = \frac{Wx^2}{24EI} (2L - x)^2. \quad (5.19)$$

The maximum deflection (y_{crit}) is at the free end and is equal to [17]

$$y_{\text{crit}} = \frac{WL^3}{24EI}. \quad (5.20)$$

The maximum stress concentration in the carry bar is found at the supported end where

$$S_{\text{crit}} = \frac{WL}{3Z} = \frac{M_{\text{max}}}{Z}. \quad (5.21)$$

The term Z in Equation (5.22) represents the simplification of the thickness and moment of inertia terms such that

$$Z = \frac{I}{c}, \quad (5.22)$$

where for a solid rectangular carriage bar,

$$I = \frac{bh^3}{12}. \quad (5.23)$$

The force that is present in the one-drive system is defined by

$$F = m(g - a). \quad (5.24)$$

5.3.2.2 Two-Drive System

The two-drive system operates with the motors running in tandem, and the carriage bar is supported and guided at both ends. The loads and moments present can be represented as shown in Figure 5.3.2.2.1. The two-drive system incorporates equal forces at both ends to maintain the vertical position and moments at both ends to maintain the zero degree departure angle from the linear guides. The deflection of the beam is the greatest at the center point as shown in Figure 5.3.2.2.1. From this two-drive system model, the stress and deflections of the beam respectively are determined to be [17]

$$S = \frac{W}{2Z} \left(\frac{1}{6} - \frac{x}{L} + \left(\frac{x}{L} \right)^2 \right) \quad (5.25)$$

$$y = \frac{Wx^2}{24EI} (L - x)^2. \quad (5.26)$$

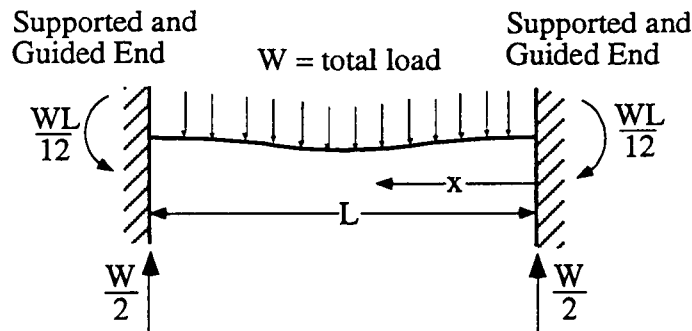


Figure 5.3.2.2.1 Forces and Moments for the Two-drive System [17]

From these equations, the maximum deflection (y_{crit}) is at the center of the beam where

$$y_{crit} = \frac{WL^3}{384EI} \quad (5.27)$$

In a similar manner, the maximum stress loads are found at the ends of the beam where

$$S_{crit} = \frac{WL}{12Z} = \frac{M_{max}}{Z} \quad (5.28)$$

The forces present at the ends for the two-drive system are exactly one half of the value as calculated in Equation (5.24).

5.3.2.3 Static Loads

The static loads of the positioner are calculated with the mechanism at a stationary point where the vertical position is being maintained. For static loads, no acceleration forces are considered in the design analysis because the system is assumed to be stationary. In order to analyze the system, some of the basic characteristics of the system need to be outlined as done for both the aluminum and steel camera carrying bars. These characteristics are given in Table 5.3.2.3.1. From the equations given in the one-drive and two-drive system sections and the characteristics given in Table 5.3.2.3.1, the static forces, moments, stresses and maximum deflections are calculated and given in Table 5.3.2.3.2.

5.3.2.4 Dynamic Loads

The dynamic loads are calculated for the condition where the system is in motion and acceleration terms greatly affect the stresses, deflections and forces present in the system. The maximum acceleration term found from the motion profile analysis completed in Section 5.3.1 was 72.2 in/sec². The acceleration term will affect the forces and moments present in the system such that the dynamic force is:

$$F_{dyn} = m(g-a) = \frac{W}{386}(g-a) \quad (5.29)$$

The moments of the system are also affected by the acceleration due to the change in the effective weight of the member. The weight of the member is affected in the same way as the force in Equation (5.29).

Table 5.3.2.3.1 Characteristics for the Camera Carrying Bar

Characteristic	Aluminum Carrying Bar	Steel Carrying Bar
Weight (W_{total}) (including scanner modules)	$W_{alum} = 46.5 \text{ lb.}$	$W_{steel} = 87 \text{ lb.}$
Length of Beam (L)	$L = 90 \text{ inches}$	$L = 90 \text{ inches}$
Distance from Neutral Axis to Extreme Fiber (c)	$c = 2.5 \text{ inches}$	$c = 2.5 \text{ inches}$
Modulus of Elasticity (E)	$E_{alum} = 9.9 - 10.3 \text{ Mpsi [13]}$	$E_{steel} = 27.6 \text{ Mpsi [13]}$
Moment of Inertia (I)	$I_{alum} = \frac{bh^3}{12} = 5.208 \text{ inches}^4$	$I_{steel} = \frac{bh^3}{12} = 5.208 \text{ inches}^4$
Width (b)	$b = 0.5''$	$b = 0.5''$
Height (h)	$h = 5.0''$	$h = 5.0''$

Table 5.3.2.3.2 Static Loads and Deflections for the Drive Systems

Condition	Aluminum Carrying Bar	Steel Carrying Bar
One-drive System Maximum Force (F_{max})	$F_{max} = W_{total} = 46.5 \text{ lb.}$	$F_{max} = W_{total} = 87 \text{ lb.}$
One-drive System Maximum Moment (M_{max})	$M_{max} = \frac{WL}{3} = 1395 \text{ in-lb}$	$M_{max} = \frac{WL}{3} = 2610 \text{ in-lb}$
One-drive System Maximum Deflection ($y_{crit.}$)	$y_{max_alum} = 0.0267 \text{ inches}$ (5.20)	$y_{max_steel} = 0.0181 \text{ inches}$ (5.20)
One-drive System Maximum Stress ($S_{crit.}$)	$S_{max_alum} = 669.6 \text{ psi}$ (5.21)	$S_{max_steel} = 1252.8 \text{ psi}$ (5.21)
Two-drive System Maximum Force (F_{max})	$F_{max} = \frac{W_{total}}{2} = 23.25 \text{ lb.}$	$F_{max} = \frac{W_{total}}{2} = 43.5 \text{ lb.}$
Two-drive System Maximum Moment (M_{max})	$M_{max} = \frac{WL}{12} = 348.75 \text{ in-lb}$	$M_{max} = \frac{WL}{12} = 652.5 \text{ in-lb}$
Two-drive System Maximum Deflection ($y_{crit.}$)	$y_{max_alum} = 0.0017 \text{ inches}$ (5.27)	$y_{max_steel} = 0.00115 \text{ inches}$ (5.27)
Two-drive System Maximum Stress ($S_{crit.}$)	$S_{max_alum} = \frac{M_{max}}{Z} =$ 167.411 psi	$S_{max_steel} = \frac{M_{max}}{Z} =$ 313.22 psi

Since the maximum acceleration term is found in both the upward and downward motions, the acceleration term which maximizes the forces and moments present in the system occurs when the acceleration is negative. In physical terms, the negative acceleration occurs as the positioner brings the camera bar to a stop on the downward motion or when the positioner accelerates the camera bar upward to return to the home position. The dynamic stress and deflections are given in Table 5.3.2.4.1 for both the one and two-drive systems.

Table 5.3.2.4.1 Dynamic Loads and Deflection for the Drive Systems

Condition	Aluminum Carrying Bar	Steel Carrying Bar
One-drive System Maximum Force ($F_{\max}$)	$F_{\max} = F_{\text{dyn}} = 55.17 \text{ lb.}$ (5.29)	$F_{\max} = F_{\text{dyn}} = 103.22 \text{ lb.}$ (5.29)
One-drive System Maximum Moment ($M_{\max}$)	$M_{\max} = \frac{WL}{3} = 1655.2 \text{ in-lb}$	$M_{\max} = \frac{WL}{3} = 3096.6 \text{ in-lb}$
One-drive System Maximum Deflection ($y_{\text{crit.}}$)	$y_{\max_alum} = 0.03218 \text{ inches}$ (5.20)	$y_{\max_steel} = 0.02181 \text{ inches}$ (5.20)
One-drive System Maximum Stress ($S_{\text{crit.}}$)	$S_{\max_alum} = 794.55 \text{ psi}$ (5.21)	$S_{\max_steel} = 1486.5 \text{ psi}$ (5.21)
Two-drive System Maximum Force ($F_{\max}$)	$F_{\max} = \frac{F_{\text{dyn}}}{2} = 27.59 \text{ lb.}$	$F_{\max} = \frac{F_{\text{dyn}}}{2} = 51.61 \text{ lb.}$
Two-drive System Maximum Moment ($M_{\max}$)	$M_{\max} = \frac{WL}{12} = 413.775 \text{ in-lb}$	$M_{\max} = \frac{WL}{12} = 774.15 \text{ in-lb}$
Two-drive System Maximum Deflection ($y_{\text{crit.}}$)	$y_{\max_alum} = 0.00201 \text{ inches}$ (5.27)	$y_{\max_steel} = 0.00136 \text{ inches}$ (5.27)
Two-drive System Maximum Stress ($S_{\text{crit.}}$)	$S_{\max_alum} = \frac{M_{\max}}{Z} =$ 198.625 psi	$S_{\max_steel} = \frac{M_{\max}}{Z} =$ 371.615 psi

5.3.3 Preliminary Design Analysis Results

The results from the preliminary design analysis indicate that the one-drive system is a feasible solution if the linear actuator can handle the eccentric loading, but the two-drive system has less loading for the linear guide to counteract. With the aluminum carry bar, the moments that the one-drive system will impose on the linear guides and ball screw is in the range of 138 ft-lb under dynamic loading, and the moments for the two-drive system are in the range of 34.5 ft-lb under dynamic loading. Although manufacturing specifications may demonstrate that either option is feasible. The one-drive system would be chosen on the basis of lower cost and the reduction of complexity of the system if the hardware to realize this design can be found.

In the analysis of the deflections and stresses in the scanner carriage bar, it was found that the deflection of the bar can be minimized by maximizing the width of the bar about the axis of rotation. This study indicated that the bar could be made taller in the direction that the load would be applied while the thickness of the bar could be reduced to achieve less deflection and better stress carrying capabilities. This analysis was performed by implementing a C language program to find the dimensions of the bar that would minimize the deflection of the bar. The C program used in this analysis is given in Appendix C.

In addition, another program was written to find the deflection and stress for the carriage bar for any specified dimensions for either the one or two-drive system. This program provided the numerical solutions given in the static and dynamic loading tables in this chapter. The program was also utilized in the detailed design as the performance of the system is optimized. This C program is given in Appendix D.

In conjunction with the calculations made in this chapter, information was gathered from experienced engineers and manufacturing specifications for the components under consideration. Regan Control was a resource for analyzing possible solutions because of

their experience with components for automation applications. Their experience provided insight into the advantages of specific components. Since velocity control is very important to the success of the inspection process, DC motors are suggested by the manufacture for applications such as this project.

The completed preliminary design analysis allowed for the feasibility of the different solutions to be assessed. This assessment allowed for a trade-off analysis to be completed where the most promising alternative was chosen for continuation.

5.4 Trade-Off Analysis Discussion

A trade-off analysis was completed in order to provide a basis for selecting the best alternative based on the most important design considerations. The design considerations for the trade-off analysis included

1. Performance: includes accuracy, reliability, system flexibility, etc.,
2. Cost,
3. Risk: includes proof of technology as well as the risk involved with the use of the component for the given application,
4. Flexibility: the ability for the system to easily adapt to changing system parameters.

Through analysis of the three conceptual designs the design solution which best matched the application was the DC motor approach. The conclusion to implement the DC motor approach was made because performance, risk and flexibility were of the most concern. The DC motor is the most conservative design approach for maximizing the performance and flexibility of the system while the risk is probably the lowest of the three possible approaches. The selection of the DC servo motor approach was supported by independent research and discussions with professors, manufacturers and fellow engineers which all

pointed to the DC motor as the design solution that would maximize the performance of the inspection process.

5.5 The Preliminary Design

The preliminary design selected by the trade-off analysis is the DC servo motor with recirculating ball screw or belt drive and linear guides alternative. The preliminary design has been developed to include the general outline and architecture of the design with some degree of insight. The developed preliminary design is shown in Figure 5.5.1 as drawn in AutoCAD release 12. The figure shows the basic configuration of the positioning system in accordance with the system design requirements. This design outline has been presented to General Shale and with their acceptance is ready for the detailed design.

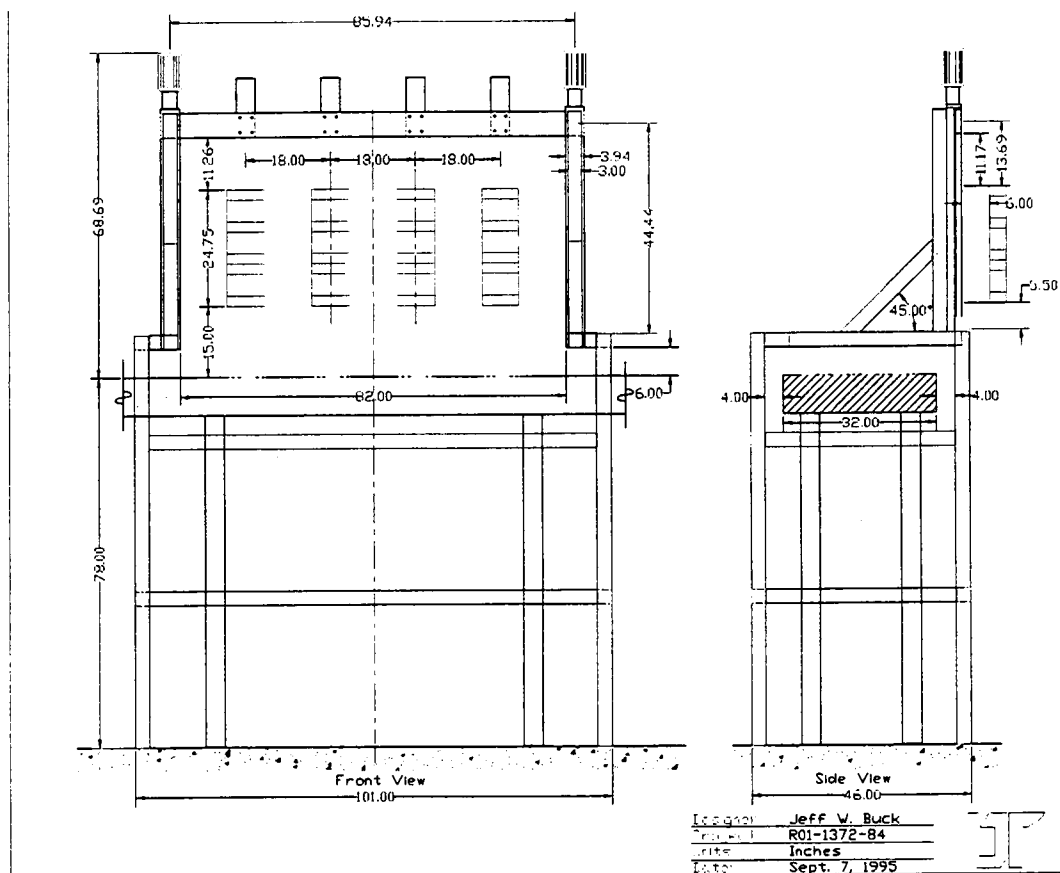


Figure 5.5.1 The Preliminary Design

Chapter Six

The Detailed Design

6.1 Introduction

At this point, the design approach has been selected as the DC servo motor with a position measurement system and fail safe brakes, in conjunction with toothed-belt drive mechanisms. Further detailed analysis to verify feasibility as well as to identify the system components is now needed. Since the DC motor alternative has been selected as the preferred option, the mathematical model for the DC motor shall be developed for analysis. The torque and speed requirements of the motor shall be found using modeling methods in conjunction with the equations that represent the physical system. Interaction with a commercial equipment supplier shall be maintained in order to determine what components would best fit the defined application and what limitations that the particular components might have. This interaction will help define whether the one-drive or two-drive system should be implemented based on performance, life and cost of available off the shelf components.

6.2 Design Decisions

In engineering scenarios, the designer has the ultimate responsibility to make decisions which define the basic characteristics of the system. The following system characteristics are based on the designer's experience, lead professor's experience and advice from manufacturers.

The moving load-carrying members of the system shall be made out of aluminum to minimize their weight. There are four scanner modules that will be carried by the 1 DoF inspection positioner. The linear actuators that will provide the one degree of freedom shall

be belt driven, and two of them will be mechanically coupled by a common shaft. The two linear actuators working in tandem will maximize the performance and life of the positioning device while also having load and moment capabilities that meet manufacturers specifications. The two belt-drive linear mechanisms will be driven by a single servo motor that will be equipped with a fail safe brake and incremental optical encoder.

6.3 Modeling the Physical System

In order to develop useful mathematical expressions which accurately represent the system, it is first required that the physical configuration of the system be defined. The physical model was developed on the assumptions given in Section 6.2, and the concept developed in Chapter Five. The physical configuration for the system is given in Figure 6.3.1 which includes all the major mechanical components required. In addition, a free body diagram of the pulley assembly is given in Figure 6.3.2. The free body diagram in conjunction with the system configuration will allow for the development of mathematical expressions which accurately represent the system.

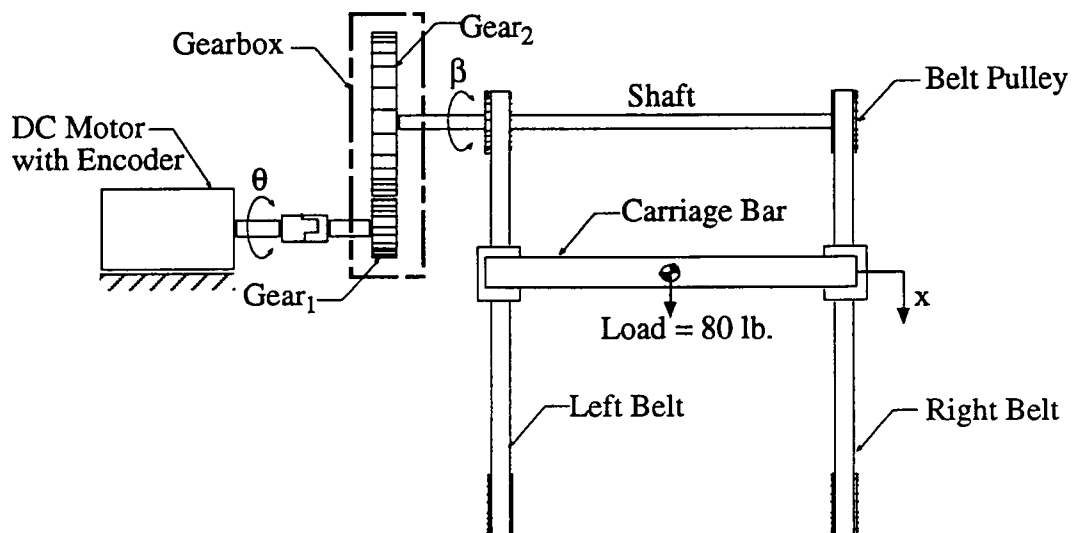


Figure 6.3.1 The Model of the Physical System

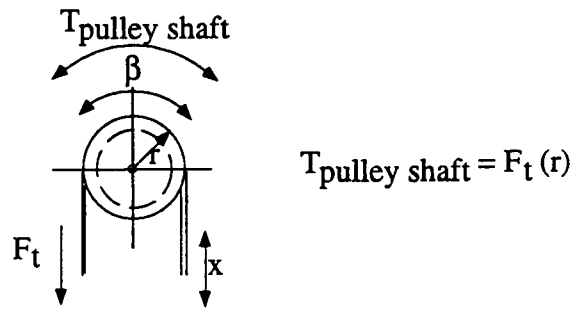


Figure 6.3.2 Free Body Diagram of Pulley Assembly

Next, the components of the system including their dynamics and kinematics must be modeled. The dynamic and kinematic models are based on the free body diagrams of the carriage bar as given in Chapter Five as well as the characteristics of the DC motor, gearbox, linear actuators and link shaft which shall be developed in this chapter.

6.3.1 Modeling the DC Servo Motor

The following equations for the DC servo motor provides a basis for defining the characteristics of the system and also gives insight into the physical system and the motor transfer function. By obtaining the DC motor transfer function which relates the input to the DC motor (voltage) to the output of the DC motor (angular velocity), the block diagram for the DC motor can be defined for implementation into the motion controller block diagram.

The development of the DC motor equations can begin with the electrical equations which represent the motor. The electrical circuit which represents the DC motor is given in Figure 6.3.1.1 which includes such motor characteristics as the motor impedance (L_a), the motor resistance (R), the current (I_a), the counter emf generated by the magnetic field (E_g) and the voltage applied to the motor.

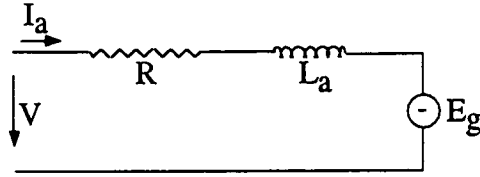


Figure 6.3.1.1 The Motor Equivalent Circuit [18]

The relationship between the electrical characteristics shown in Figure 6.3.1.1 is [18]

$$V_e = I_a R + L_a \frac{dI_a}{dt} + E_g \quad (6.1)$$

where E_g can be defined as

$$E_g = K_e \omega . \quad (6.2)$$

As the motor produces a constant magnetic field, the current in the motor produces a proportional torque [18]

$$T_g = K_t I_a \quad (6.3)$$

The opposing torque in the motor is given by

$$T_m = T_F + D\omega \quad (6.4)$$

where D represents all the viscous friction torques which are proportional to the motor velocity and T_F represents friction torque. If the motor is coupled to a load, the torque which the motor can be evaluated as:

$$T_g = (J_m + J_L) \frac{d\omega}{dt} + D\omega + T_f + T_L \quad (6.5)$$

where T_L represents the torque due to the load. Next, the inertial components found in Equation (6.5) can be combined so that

$$J = J_m + J_L . \quad (6.6)$$

Applying Laplace transform methods [19], the following motor equations can be formed [18]:

$$V_e(s) = (sL_a + R)I_a(s) + K_e\omega(s) \quad (6.7)$$

$$T_g(s) = K_t I_a(s) \quad (6.8)$$

$$T_g(s) = (J_m + J_L)s\omega(s) + D\omega(s) \quad (6.9)$$

Now by substitution and rearrangement, the following equations are obtained:

$$I_a(s) = \frac{1}{K_t} (sJ + D)\omega(s) \quad (6.10)$$

$$V_e(s) = \frac{1}{K_t} (sL_a + R)(sJ + D)\omega(s) + K_e\omega(s) \quad (6.11)$$

The corresponding transfer function for the motor is [18]

$$G_m = \frac{\omega(s)}{V_e(s)} = \frac{K_t}{(sL_a + R)(sJ + D) + K_e K_t} \quad (6.12)$$

The transfer function dynamically relate the speed of the motor to the input voltage for the unloaded case. The block diagram for the transfer function given in Equation (6.12) is shown in Figure 6.3.1.1. Many times in actual applications, interaction with the environment and loading conditions cause the transfer function to be a function not only of voltage but also of the motor load or system disturbance [20]. When load effects are included, the motor transfer function becomes

$$G_m = \omega(s) = \frac{K_t V_e(s)}{(sL_a + R)(sJ + D) + K_e K_t} + \frac{(L_a s + R)T_L}{(sL_a + R)(sJ + D) + K_e K_t} \quad (6.13)$$

which corresponds to the block diagram shown in Figure 6.3.2.1. The sign of the load torque (T_L) depends on the direction that the torque is applied. If the load torque resists the motion of the motor, then the sign of the load torque is negative, but if the load torque assists the motion of the motor, then the sign is positive.

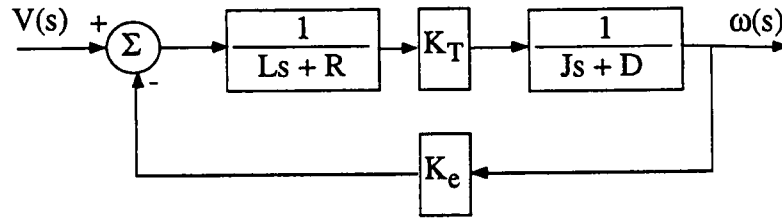


Figure 6.3.1.1 The Block Diagram for a DC Motor

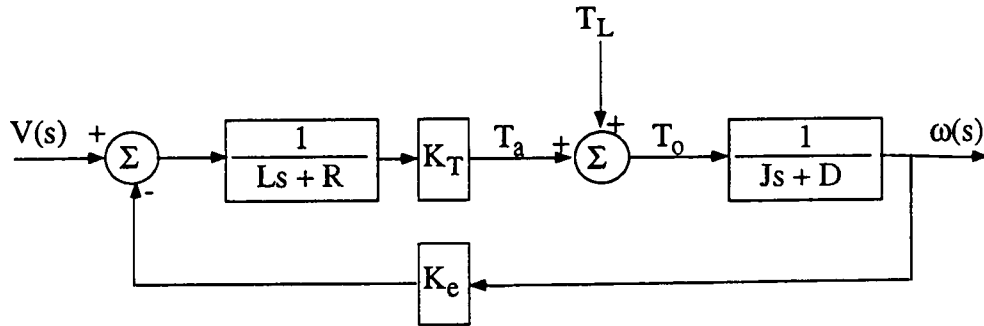


Figure 6.3.2.1 The Block Diagram for a DC Motor with a Load Torque Applied

6.3.2 Determining the Speed Requirements for the Motor

The speed requirements of the motor are a function of the translational speed of the slider of the linear actuator and the gear ratio back to the motor shaft. For this application, it was determined in Chapter 5 that the maximum translation speed for the slider was approximately 12.5 in/sec. The belt drive mechanism converts motor rotation into load translation such that

$$x = r\beta. \quad (6.14)$$

where β represents the shaft position of the pulley and x represents the carriage position. Therefore, the translational velocity and acceleration of the carriage bar can be related to the rotational velocity and acceleration of the shaft by taking the derivative of Equation (6.14).

The ratio of the position of the shaft of the pulley and the shaft of the motor can be found as

$$\theta = \frac{d_2}{d_1} \beta = N \beta, \quad (6.15)$$

where

$$N = \frac{d_2}{d_1} . \quad (6.16)$$

Now, the transitional position of the slider can be found as a function of the motor shaft position by substitution of Equation (6.14) and (6.15). The resulting relationship between the carriage bar position (x) and the motor shaft position (θ) is defined as

$$x = \frac{r}{N} \theta . \quad (6.17)$$

6.3.3 Determining the Torque Requirements for the Motor

The torque requirement for the motor is developed from the equations representing the DC motor and the physical system with which the motor must interact. The sketch of the physical system is shown in Figure 6.3.1, and the modeling equations for the system are taken from Figure 6.3.1.

In order to evaluate the required torque that the motor must deliver, the inertial load that is reflected back to the motor shaft must be found. Summation of the kinetic energy terms found in the system will provide a method for accomplishing the goal of finding the effective inertial load felt at the motor shaft. For rotating members, the kinetic energy can be expressed as

$$KE_{\text{rotational}} = \frac{1}{2} I_{\text{eff}} \omega^2 . \quad (6.18)$$

where I_{eff} is the effective inertial load.

For translating members, the kinetic energy can be expressed as

$$KE_{\text{translational}} = \frac{1}{2} m \dot{x}^2 . \quad (6.19)$$

Summation of the kinetic energy parts for the physical system as shown in Figure 6.3.1 yields

$$KE = \frac{1}{2} I_{\text{eff}} \omega^2 = \frac{1}{2} I_{\text{motor}} \omega^2 + \frac{1}{2} \frac{I_{\text{gearbox}}}{\eta} \omega^2 + \frac{1}{2} I_{\text{shaft}} \left[\frac{\omega}{N} \right]^2 + \frac{1}{2} I_{\text{actuators}} \left[\frac{\omega}{N} \right]^2 + \frac{1}{2} m \dot{x}^2 . \quad (6.20)$$

From Equation (6.20), the effective inertial load can be found as

$$I_{\text{eff}} = I_{\text{motor}} + \frac{I_{\text{gearbox}}}{\eta} + \frac{I_{\text{shaft}}}{N^2} + \frac{I_{\text{actuators}}}{N^2} + m \left[\frac{r}{N} \right]^2 . \quad (6.21)$$

Now that the effective inertial load of the system has been found, the torque requirements for the motor can be found by applying D'Alembert's principal [21] which yields

$$\Sigma T = I \ddot{\theta} . \quad (6.22)$$

By applying Equation (6.29) to the physical system, the following expression for the torques can be found:

$$\Sigma T = T_m + T_L = I_{\text{eff}} \ddot{\theta} . \quad (6.23)$$

where

$$T_L = - \left[\frac{W r}{N} \right] . \quad (6.24)$$

By combining Equations (6.23) and (6.24), the torque of the motor can be evaluated as

$$T_m = I_{\text{eff}} \ddot{\theta} + W \left[\frac{r}{N} \right] \quad (6.25)$$

where $I_{\text{eff}} \ddot{\theta}$ represents the acceleration terms of the torque felt at the motor, and T_L represents the static load which the motor must overcome to maintain the correct vertical position while the system is stationary or traveling at a constant velocity.

At this point, the motor torque can be found by evaluating Equation (6.25) for the system with the components that have been selected. The torque required by the motor for the given application is now determined, but finding the motor that suits the application is an iterative process. The motor and the system components all dictate the torque requirements placed on the motor, and changing one component can change the torque requirements.

6.4 Component Selection

Component selection is an iterative process, and the final results are given in Table 6.4.1. By defining the key mechanical components of the system, the motor can be sized based on the torque requirements of the system. A motor must also be selected at this point and analyzed to verify that it will satisfy the system requirements.

Table 6.4.1 Mechanical Components of the System

Component	Manufacturer	Part Number	Comments
Linear Actuator: Left Side	Hauser	L10Y1150DL21SS	HLE100A: 1150 mm travel
Linear Actuator: Right Side	Hauser	L10Y1150LS21SS	HLE100A: 1150 mm travel
Link Shaft	Hauser	————	Mechanically Link Actuators
Proximity Sensor	Hauser	————	Home Position Locator
Limit Switches	Hauser	————	Overrun Switches (2)
Planetary Gearbox	Hauser	PL90 N10	Gear Ratio of 10
Servo-Motor	Yaskawa	SGM-08	with inc. encoder and brake
Servo-Motor Controller	Yaskawa	SGDA-08A	amplifier/controller

The components given in Table 6.4.1 were selected based on interaction with engineers, manufacturers and distributors, as well as applicability to the given application. In the following sections, the selection of the components will be verified based on analysis of the system model. Next, the system shall be analyzed and verified based on the design as completed.

6.5 System Analysis

The scanner carriage bar has been revised from its state in Chapter 5 to the design shown in Figure 6.5.1. The custom design for the scanner carriage bar was selected over a prefabricated extrusion bar to minimize the deflection about the y-axis (see Figure 6.5.2) while also having better aesthetics. Since the revisions of the carriage bar affect many of the system characteristics, it is analyzed in the beginning of the system analysis. The change in the carriage bar was precipitated by a change in the plant layout which required that the bar be shortened. The revision of the carriage bar will change the weight of the system and also the deflections and stress in the carriage bar. The new carriage bar has a total weight of approximately 60 pounds which includes the carriage bar and four scanner models. If a design margin of 33% is added to account for cables and other unknowns, the design weight for the new carriage bar will be approximately 80 lb.

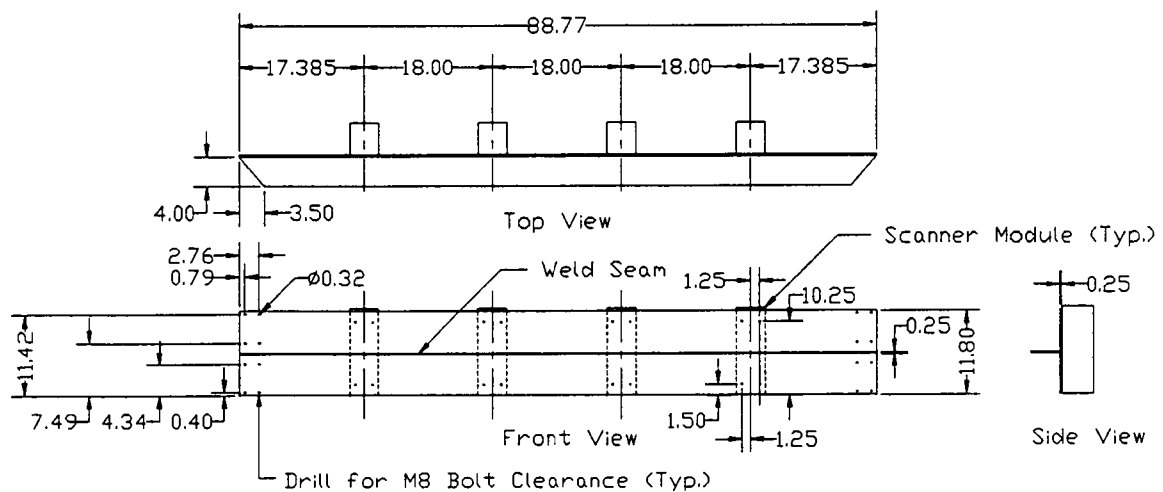


Figure 6.5.1 The Revised Camera Carriage Bar with Scanner Modules

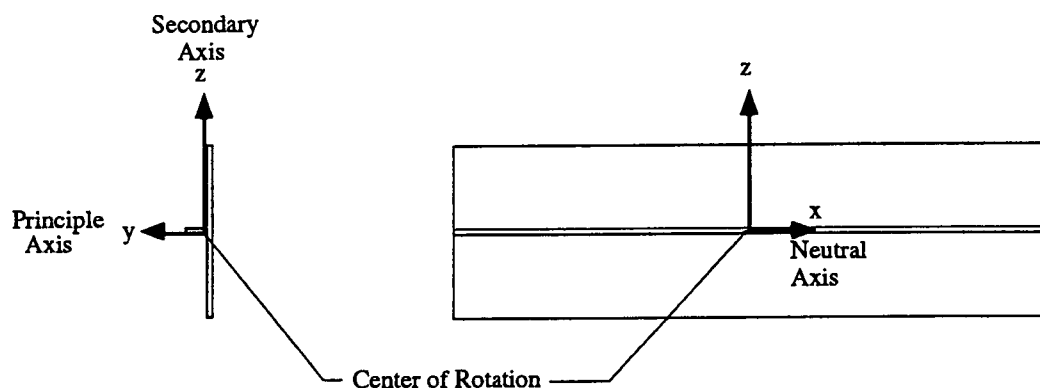


Figure 6.5.2 The Carriage Bar with Coordinate System Attached

The design of the inspection station has undergone many iterations and revision which have lead to the selection of components which have the mechanical properties as given in Table 6.5.1. By analyzing the system with these properties, the feasibility of this combination of components can be tested. In Table 6.5.1, each component of the drive train is listed along with its respective inertial properties. By substituting the values given in Table 6.5.1 into Equation (6.21), the effective inertial load felt at the motor shaft is found to be $I_e = 1.6468 \text{ lb}_m\text{-in}^2$.

Table 6.5.1 Inertial Properties for Drive System Components

Component	Inertia
Carriage Bar	$W = 80 \text{ lb.}$
Linear Actuators (each) ($r = 1.065''$)	$I_{\text{actuators}} = 5.9 \text{ lb}_m\text{-in}^2$
Mechanical Linkage Shaft	$I_{\text{shaft}} = 3.215 \text{ lb}_m\text{-in}^2$
Planetary Gearbox ($\eta = 92\%$, $N = 10$)	$I_{\text{gearbox}} = 0.2869 \text{ lb}_m\text{-in}^2$
Servo Motor	$I_{\text{motor}} = 0.2774 \text{ lb}_m\text{-in}^2$
Effective inertia of the system	$I_e = 1.6468 \text{ lb}_m\text{-in}^2$

6.5.1 Torque and Speed Characteristics of the System

The effective inertia found in the previous section allows for the torque requirement of the motor to be found as shown in Equation (6.25). The maximum torque that the motor will be required to generate will occur when the weight and inertia load are additive carriage bar is accelerated upward as the carriage returns to the home position. The maximum torque that the motor must produce occurs at maximum acceleration ($a_{\max} = 72.7 \text{ in/sec}^2$ as found in Chapter Five) of the carriage bar. Under this condition, the maximum required motor torque is found to be $T_m = 11.41 \text{ in-lb}_f$. The Yaskawa servo-motor specified for this application has a rated torque capacity of 21.125 in-lb_f at the rated speed of 3000 rpm. Therefore, the selected motor in conjunction with the specified mechanical components has a 82.3% design margin with respect to the torque of the motor.

By using the equations developed in Section 6.3.2, a maximum motor speed of approximately 1123.5 rpm was obtained. The rotational speed of the pulley shaft that links the two linear actuators together was found to be 112.35 rpm since the gear ratio between the input and output is 10.

Table 6.5.1.1 The Torque and Speed Characteristics of the System

Characteristic	Calculated Value
Maximum acceleration of the slider	$a_{\max} = 72.2 \text{ in/sec}^2$
Maximum torque required for the given application and system configuration	$T_m = 11.41 \text{ in-lb}_f$
Design margin for the motor	$D_m = 82.3\%$
Rotational speed of the motor	$\omega_{\text{motor}} = 1123.5 \text{ rpm}$
Rotational speed of the link shaft	$\omega_{\text{link shaft}} = 112.35 \text{ rpm}$

6.5.2 Force, Moment, Deflection and Stress Analysis

The carriage bar configuration will impact the force, moment, deflection and stress loads that the mechanical structure must be able to withstand. Before the analysis of the mechanical characteristics of the system can be completed, the inertias about the principal and secondary axis must be found for further analysis. Once the inertias of the system are found, the loading conditions about the principal and secondary axis must be defined which also defines the spring rate, deflection and stress of the carriage bar.

Since the carriage bar has vertical and horizontal rectangular sections (See Figure 6.5.1), the effective moment of inertia about the principal can be found by simply adding the inertias of the two rectangular sections together since they both rotate about an axis which is located at their centroid. Therefore, the inertia of the carriage bar about the principal axis can be written as

$$I_y = I_{11.8"} y + I_{4"} y \quad (6.26)$$

where

$$I_{11.8"} y = \frac{0.25 * 11.8^3}{12} = 34.23 \text{ in}^4, \text{ and} \quad (6.27)$$

$$I_{4"} y = \frac{4.0 * 0.25^3}{12} = 0.0052 \text{ in}^4 . \quad (6.28)$$

By inspection, it becomes obvious that the inertia for the 4" wide section is negligible about the principal axis. Therefore, the effective moment of inertia that is responsible of supporting the load of the scanner modules is the inertia from the 11.8" high rectangular section. The effective moment of inertia about the secondary axis can be found by applying

$$I_0 = I + md^2 \quad (6.29)$$

where I_0 is the inertia of the system about the axis of rotation, and I is the inertia of the member, m is the mass of the member and d is the distance from the centroid of the member to the axis of rotation. Therefore, the inertia of the carriage bar about the secondary axis can be written as

$$I_z = I_{11.8"} z + m_{11.8"} (d_1)^2 + I_{4"} z + m_{4"} (d_2)^2 \quad (6.30)$$

where

$$I_{11.8'' z} = \frac{11.8 * 0.25^3}{12} = 0.01536 \text{ in}^4, \text{ and} \quad (6.31)$$

$$I_{4'' z} = \frac{0.25 * 4.0^3}{12} = 1.333 \text{ in}^4. \quad (6.32)$$

The distances d_1 and d_2 were found to be 0.538" and 1.587" respectively as determined from the model shown in Figure 6.5.2.1. The distances d_1 and d_2 were proportional to the weights of the two rectangular bars. The mass of the combined carriage bar was $0.20725 \frac{\text{lb-sec}^2}{\text{in}}$.

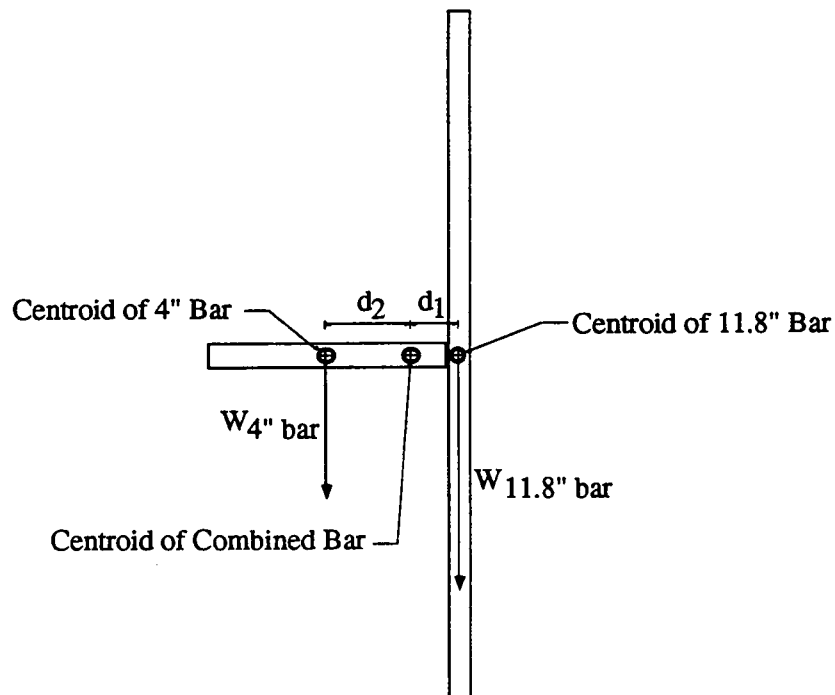


Figure 6.5.2.1 The Model Used to Determine d_1 and d_2

Although the 4" wide rectangular section does not aid much in supporting the mechanical load, it increases the stiffness of the beam in the direction perpendicular to the direction of the load which will minimize deflections and vibrations that might be induced.

By minimizing the deflections and vibrations of the beam, the performance of the image analysis will be maximized which is the ultimate goal of the project. In Table 6.5.2.1, the inertias of the revised camera carriage bar are given.

Table 6.5.2.1 Inertial Values for the Revised Camera Carrying Bar

Characteristic	Inertial Value
Moment of Inertia (I_y) about the principal axis	$I_y = 34.23 \text{ inches}^4$
Moment of Inertia (I_z) about the secondary axis	$I_z = 1.424 \text{ inches}^4$

Now that the inertial properties for the carriage bar have been defined, the loading and deflection conditions about the principal axis and secondary axis are found which defines the spring rate, deflection and stress capacities of the beam. The loading conditions about the principal axis (the y-axis in Figure 6.5.2) is shown in Figure 6.5.2.2, which shows the two drive system modeled as a simple beam which has two fixed ends with a uniform distributed load across the carriage bar due to the weight of the beam and scanner modules. The loading conditions about the secondary axis (the z-axis in Figure 6.5.2) is shown in Figure 6.5.2.3 which accounts for a point load applied to the carriage bar at the center of the beam. The point load that is applied to the carriage bar to cause deflections about the z-axis will affect the stand-off distance between the laser scanner and the brick being inspected. The load is modeled as a point load since the weight of the beam does not affect the beam about the z-axis but some type of point load could be encountered in the operation of the positioner. The point load would typically be some type of impulse load that would induce motion about the z-axis.

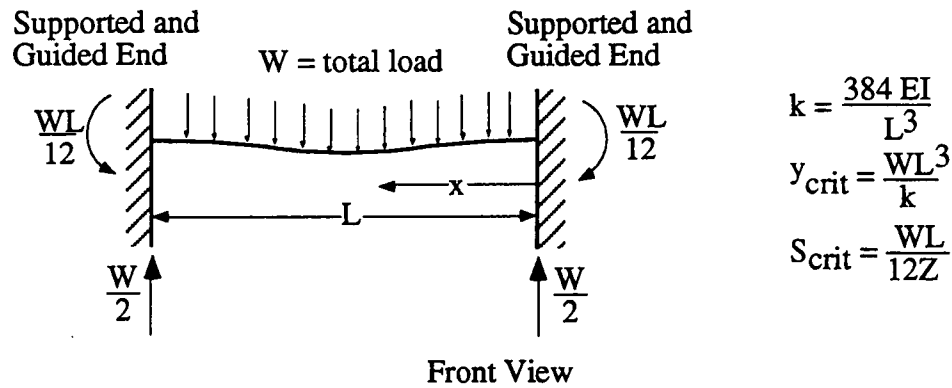


Figure 6.5.2.2 The Loading Model of the System about the Principal Axis (y-axis)

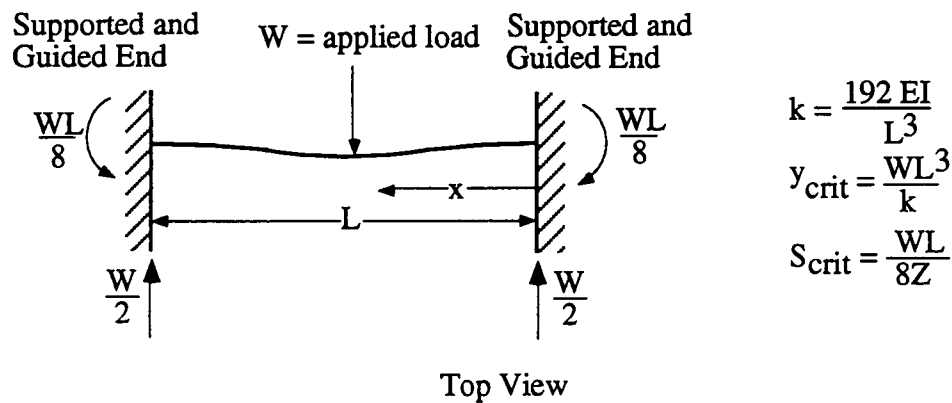


Figure 6.5.2.3 The Loading Model of the System about the Secondary Axis (z-axis)

With the loading conditions defined, the spring rate, deflections, stresses and natural frequencies of the carriage bar can be calculated. In Table 6.5.2.2, the carriage bar characteristics are determined, and the loads, length of the bar and material properties of the bar are defined. The stiffness values for the beam are taken from the stiffness equations shown in Figures 6.5.2.2 and 6.5.2.3. The natural frequency of the carriage bar is representative of the vibration characteristics of the bar where high natural frequencies indicate small vibrations. Both the static and dynamic loading conditions about the principal axis of the carriage bar were calculated as shown in Table 6.5.2.3 which corresponds to the modeled system shown in Figure 6.5.2.2. The loading conditions

about the secondary axis were calculated as shown in Table 6.5.2.4 where a 10 pound point load applied to the carriage as modeled in Figure 6.5.2.3.

Table 6.5.2.2 Mechanical Characteristics for the Revised Camera Carrying Bar

Characteristic	Parameter Value
Design Weight (weight includes scanner modules)	$W_{\text{total}} = 80 \text{ lb.}$
Point load applied to the carriage bar to induce motion about the z-axis	$W_{\text{point load}} = 10 \text{ lb.}$
Length of Beam (L)	$L = 81.3 \text{ inches}$
Modulus of Elasticity (E)	$E_{\text{alum}} = 9.9 - 10.3 \text{ Mpsi [16]}$
Stiffness (k_y) of Beam about the principal axis	$K_y = 2.446 \times 10^5 \frac{\text{lb}_f}{\text{in}}$
Stiffness (k_z) of Beam about the secondary axis	$K_z = 5087.9 \frac{\text{lb}_f}{\text{in}}$
Natural Frequency (ω_{ny}) about the principal axis	$\omega_{ny} = 1086.4 \frac{\text{rad}}{\text{sec}}$
Natural Frequency (ω_{nz}) about the secondary axis	$\omega_{nz} = 156.68 \frac{\text{rad}}{\text{sec}}$
Oscillating Frequency (f_{ny}) about the principal axis	$f_y = \frac{\omega_{ny}}{2\pi} = 173 \text{ Hz}$
Oscillating Frequency (f_{nz}) about the secondary axis	$f_z = \frac{\omega_{nz}}{2\pi} = 25 \text{ Hz}$

Table 6.5.2.3 Static and Dynamic Loading of the System about the Principal Axis

Condition	Static Loading	Dynamic Loading
Maximum Force (F_{max})	$F_{\text{max}} = \frac{W_{\text{total}}}{2} = 40.00 \text{ lb.}$	$F_{\text{max}} = \frac{W_{\text{total}}}{2} = 47.48 \text{ lb.}$
Maximum Moment (M_{max})	$M_{\text{max}} = \frac{WL}{12} = 591.8 \text{ in-lb}$	$M_{\text{max}} = \frac{WL}{12} = 702.5 \text{ in-lb}$
Maximum Deflection ($y_{\text{crit.}}$)	$y_{\text{max alum}} = 0.000426''$	$y_{\text{max steel}} = 0.000505''$
Maximum Stress ($S_{\text{crit.}}$)	$S_{\text{max alum}} = \frac{M_{\text{max}}}{Z} =$ 102.0 psi	$S_{\text{max steel}} = \frac{M_{\text{max}}}{Z} =$ 121.1 psi

Table 6.5.2.4 Loading of the System about the Secondary Axis for a Given Point Load

Condition	Parameter
Maximum Force ($F_{\max}$)	$F_{\max} = \frac{W_{\text{point load}}}{2} = 5.00 \text{ lb.}$
Maximum Moment ($M_{\max}$)	$M_{\max} = \frac{WL}{8} = 101.625 \text{ in-lb}$
Maximum Deflection ($y_{\text{crit.}}$)	$y_{\max_alum} = 0.001965''$
Maximum Stress ($S_{\text{crit.}}$)	$S_{\max_alum} = \frac{M_{\max}}{Z} =$ 142.73 psi

The results presented in Tables 6.5.2.2, 6.5.2.3 and 6.5.2.4 show the performance of the carriage bar under loading conditions most likely encountered in the actual application. All of the calculated parameters are within the specifications and requirements for the carriage bar as well as manufactures specifications for the linear actuators.

The static deflection of the carriage bar about the secondary axis was studied to analyze if the deflections of the beam under normal conditions would degrade the inspection process. The maximum resolution of the AccuRange laser scanner is approximately $\pm 1 \text{ mm}$ so deflections of the beam significantly less than that will not degrade the scanning. In Figure 6.5.2.4, the deflection of the carriage beam about the secondary axis versus the load applied to the beam is plotted. The results of the study showed that the range of realistic static loads caused a deflection only one tenth of the scanner resolution.

The dynamic loading of the carriage bar that would induce vibrations was modeled as an impulse inducing load. For the dynamic condition, the carriage bar can be modeled as a simple spring mass system with negligible damping. The equation of motion for the spring mass system with a forcing function can be expressed as

$$m \ddot{x} + k x = f \quad (6.33)$$

where f is the impulse load which induces vibrations in the system. The mass of the bar is $0.20725 \frac{\text{lb-sec}^2}{\text{in}}$, and the stiffness of the bar about the secondary axis is $5087.9 \frac{\text{lb}_f}{\text{in}}$. By

applying Laplace transform methods, Equation (6.33) can be rewritten as

$$X(s) (s^2 + \frac{k}{m}) = \frac{f}{m} \quad (6.34)$$

which has the inverse Laplace transform of

$$x(t) = \frac{1}{m\omega_n} \sin(\omega_n t) . \quad (6.35)$$

When Equation (6.35) is evaluated, the maximum value of $x(t)$ is found as 0.0308 inches (0.78 mm) which is smaller than the maximum resolution of the laser scanner. Therefore, the scanner carriage bar have been designed with sufficient stiffness characteristics that the vibrations and deflections of the system will have no appreciable degradation of the scanning process.

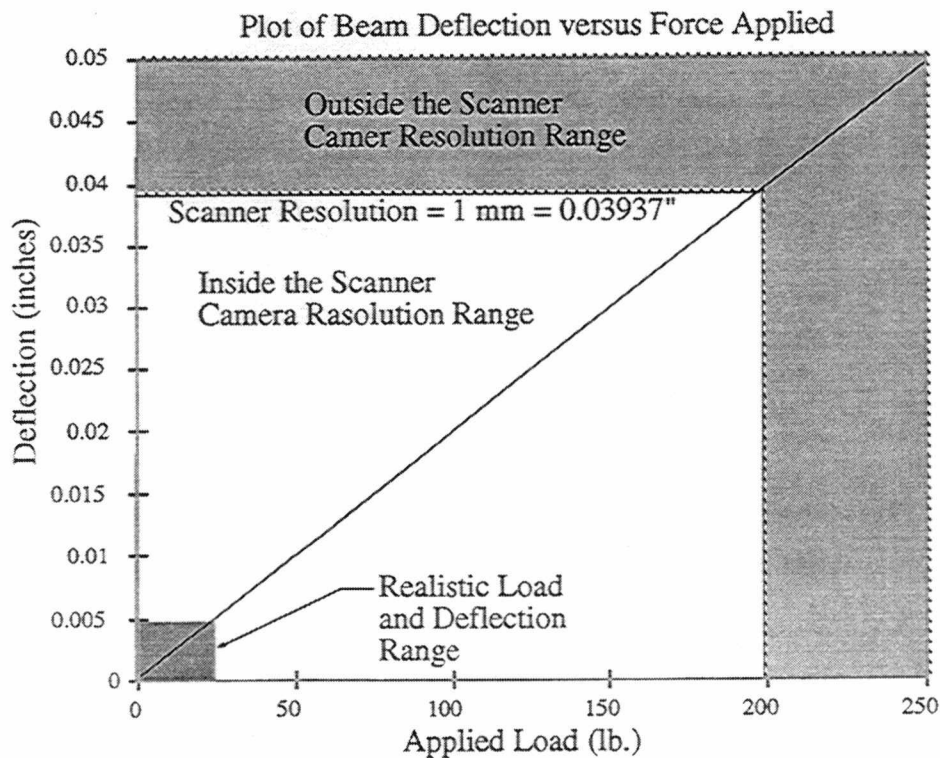


Figure 6.5.2.4 Plot of Beam Deflection about the Secondary Axis Versus Applied Load

The analysis completed on the mechanical components of the positioner was to verify the feasibility of the design solution. The results obtained through the mechanical analysis verifies that the mechanical positioner will meet the design requirements and will not appreciably degrade the inspection process.

6.6 Controller Design

6.6.1 Control Approach

At this point in the system analysis and design, the motor block diagram has been developed without consideration of how it would be controlled. Now it is time to surround the motor with the control hardware and software which will allow for control of the scanner positioner. For the DC motor controller, a closed loop controller must be implemented by using the feedback generated by the motor shaft incremental encoder. In order to accomplish the control of the DC motor, the hardware must be selected which will be used to control the system, and the control laws that will be implemented into software must be developed. The development of the control laws for the controller is performed in the control system analysis and simulation section of this chapter (Section 6.6.3).

To begin the selection of the controller, the basic architecture of the controller and the roles that the peripheral devices must be defined. For this application, the control approach is based on the desire to maintain a high level of flexibility for future optimization of the inspection station once the image analysis system is integrated. The controller for the system will be responsible for the sequence of events that take place during the inspection of the brick while providing motion control for the positioning mechanism. The controller may also perform the image analysis or communicate with another CPU performing the image analysis on the brick being inspected. With many unknowns remaining, the controller has been selected based on optimal flexibility, customer preference and cost.

The method of control chosen for the inspection station is a central control station that communicates with peripheral systems such as the motion controller, limit switches, image analysis system, BUPS and HMI. The primary elements of the inspection station controller are shown in Figure 6.6.1.1.

The control laws that will be implemented in the motion controller portion of the inspection station will be developed to maximize the performance of the inspection station while maintaining a high level of flexibility. At this point, the hardware for the system has been defined, but software must be developed to control the hardware. Since software adds almost no cost compared to the hardware, special care is given to maximize the performance of the controller, although analysis will show that simpler control strategies could be implemented. The performance of the uncompensated and compensated system will be compared for verification that the compensated outperforms the uncompensated system. In order to perform the analysis of the positioning system, the positioning system, motor and encoder are modeled and simulated. MATLAB and SIMULINK application programs [10] were used to perform the simulation and analysis of the control system.

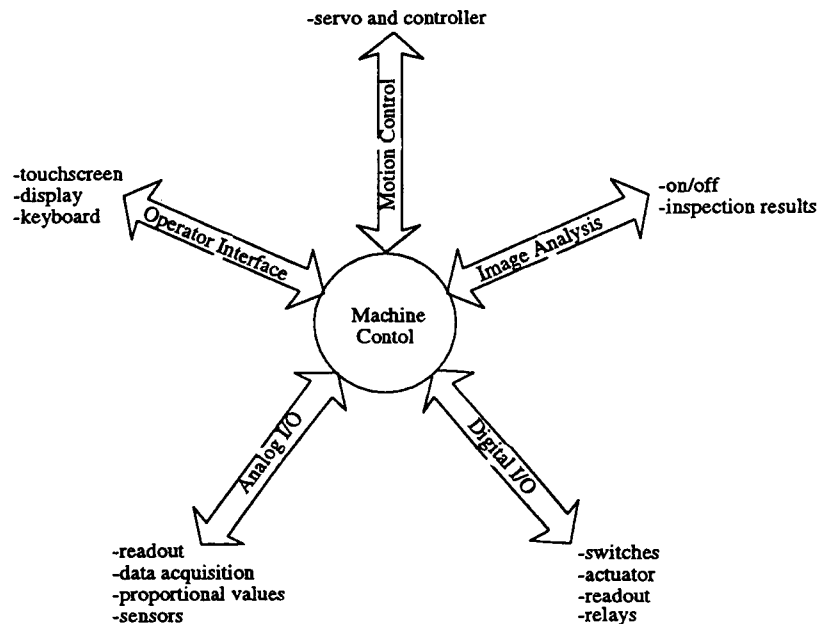


Figure 6.6.1.1 The Primary Machine Control Elements of the Controller [22]

6.6.2 Controller Hardware

The hardware that will maximize the flexibility of the system while also keeping cost reasonable is the PC based control system. The PC controller is also preferable by the customer due to more experience with the PC hardware versus VME and other bus type hardware. Although the customer has a great deal of experience with the PLC, it does not provide the flexibility required. The PC controller selected is the Pro-Log PI486V industrial computer with the following capabilities; 120 MHz clock speed, 512 KB cache, 760-15-250A industrial chassis, 1.44 MB 3.5" floppy drive, HD-002 1.2 GB IDE hard drive and spill resistant keyboard. This computer system interfaces with the numerous and reasonably priced PCI and ISA electronic cards, and these type of cards can be added to the system for whatever need arises. One such possibility is a video frame grabber for data acquisition from the scanners. The HMI for the OCS is the Xycom 9450-SSW SoftScreen Workstation which has touchscreen capabilities.

6.6.3 Analysis and Simulation

Only by analysis and simulation can the motion control system be identified and designed to perform as required. Analysis of the control system begins with identification of the block diagram that corresponds to the physical system. The controller model shown in Figure 6.6.1 is developed from the equations and relationships that represent the physical system. The model has the desired position of the carriage as the input and the actual position of the carriage as the output. The load and friction torques have been integrated into the model to represent the load that is applied to the system by the scanners and the scanner carriage as well as the motor friction.

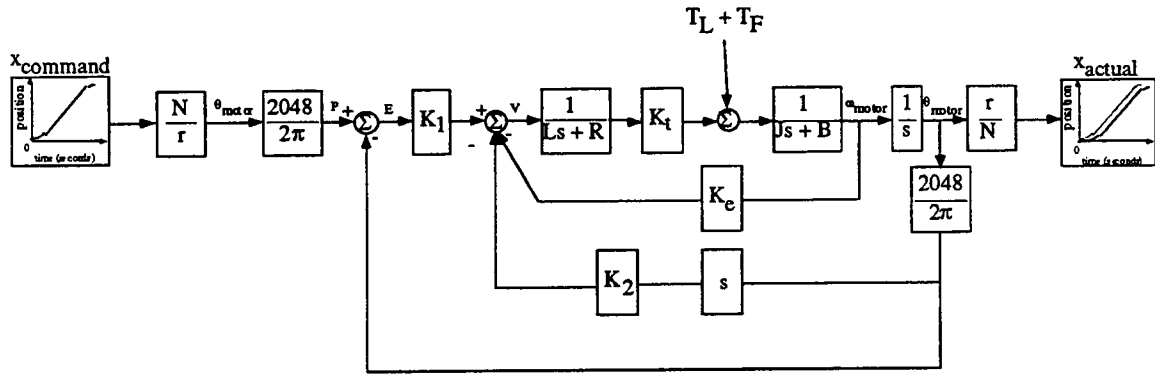


Figure 6.6.3.1 The Block Diagram Model for the Motion Controller

The block diagram allows for analysis of the controller and determination of the gain values K_1 and K_2 which are determined by the designer in order to achieve the desired response. By analyzing the controller block diagram using signal flow diagrams and Mason's Gain Rule [23], the transfer function that represents the model is found to be:

$$x_{\text{actual}} = \frac{K_1 K_t \left[\frac{2048}{2\pi} \right] * x_{\text{command}} + \left[\frac{r}{N} \right] (Ls + R) (T_L + T_F)}{LJs^3 + s^2(JR + LB) + s(RB + K_2 K_t \left[\frac{2048}{2\pi} \right] + K_c K_t) + K_1 K_t \left[\frac{2048}{2\pi} \right]} \quad (6.36)$$

The system type is found to be 0 which indicates that a finite steady state error is obtained for a unit step input. Since the input into the controller will sometimes be a parabolic input, the system must be compensated to at least a type 2 system which will have a finite steady state error for a parabolic input. In order to compensate the system such that it becomes a type 2 system, a double PI controller [23] can be implemented. When the system is a type 2 system, the system will have a zero steady state error for a ramp or step input and can be designed to have a small but finite steady state error for a parabolic input. The order of the system is determined by the number order of the "s" variables found in

the denominator of the transfer equation where the "s" variable is defined as the Laplace differential operator.

The PI controller can be represented as

$$G_c = \frac{K_p s + K_i}{s} \quad (6.37)$$

where K_p is the proportional gain and K_i is the integral gain. As seen in Equation (6.37), the PI controller places a pole at origin of the root locus plot and has a zero at $-K_i/K_p$. This zero and pole placement in the root locus of the PI controller has the effect of slowing the response time of the system but reducing the steady state error. By implementing two of the PI controllers, the new system will take the form of a type two system and has the transfer function

$$x_{\text{actual}} = \left[\frac{K_p s + K_i}{s} \right]^2 * \frac{K_1 K_t \left[\frac{2048}{2\pi} \right] * x_{\text{command}} + \left[\frac{r}{N} \right] (Ls + R) (T_L + T_F)}{LJs^3 + s^2(JR + LB) + s(RB + K_2 K_t \left[\frac{2048}{2\pi} \right] + K_e K_t) + K_1 K_t \left[\frac{2048}{2\pi} \right]} \quad (6.38)$$

The block diagram shown in Figure 6.6.4.2 represents the block diagram with the new compensator as in Equation (6.38).

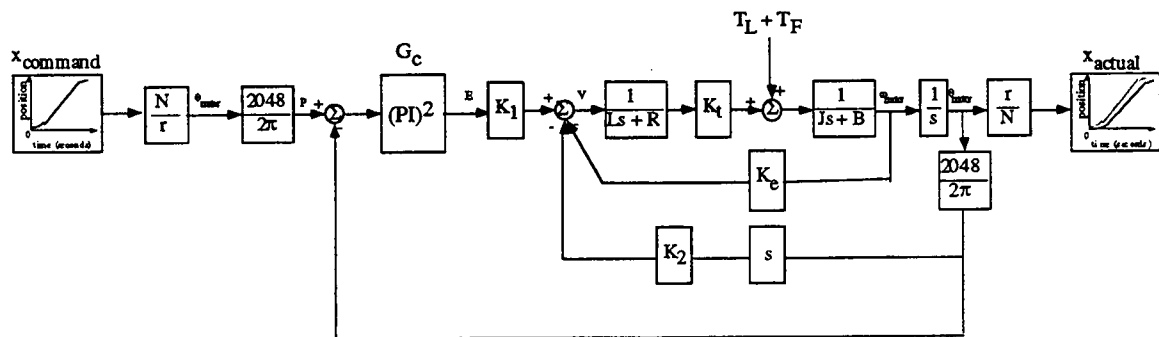


Figure 6.6.3.2 The Double PI Compensated Block Diagram

The simulation of the motion controller has been developed by representing the block diagram shown in Figure 6.6.3.2 using MATLAB and SIMULINK application programs [10]. These programs allow for classical control methods [23] to be applied to the model to determine the output of the system for a specified input. A sample MATLAB program used for control system analysis is given in Appendix E which shows the capability for root locus, frequency response and transient response analysis. For the MATLAB and SIMULINK simulation, all of the variables shown in Figure 6.6.3.1 and Figure 6.6.3.2 have been identified from analysis and manufacturers specifications. In Table 6.6.3.1, the variables and their corresponding values are given.

Table 6.6.3.1 Block Diagram Parameter Values

Description	Variable	Value
Gear ratio	N	10
Pulley Radius	r	1.065"
Winding Inductance	L	0.0057 Henrys
Winding Resistance	R	0.45 Ω
Motor Constant	K_t	5.21875 $\frac{\text{in-lb}}{\text{A}}$
Voltage Constant	K_e	0.1967 $\frac{\text{V-sec}}{\text{rad}}$
Effective Inertia	J	0.004266 $\text{lb}_f\text{-in-s}^2$
Damping	B	≈ 0
Load Torque	T_L	Equation (6.32) $\approx 11.5 \text{ in-lb}_f$
Weight	W	80 lb_f
Gravity	g	386 $\frac{\text{in}}{\text{sec}^2}$
Friction Torque	T_F	0.3369 in-lb_f

Using the values given in Table 6.6.3.1, the model of the system can be evaluated using MATLAB and SIMULINK. The SIMULINK model used to analyze the controller is shown in Figure 6.6.3.3.

By testing the simulation model, the gain values of the system have been determined. For a step input into the uncompensated system, K_1 and K_2 are determined by finding the respective values that give the transient response desired. The results of this analysis gave K_1 a value of 0.01 and K_2 a value of 0.00001. A comparison of the input and output are given in Figure 6.6.4.4 where the system is uncompensated and $K_1 = 0.01$ and $K_2 = 0.00001$, and the system input is a unit step input. It should be noted that there is no unique solution for the gain values, but the designer can set the gains to achieve an acceptable transient response. In addition to the SIMULINK model, a MATLAB program has been written to analyze the system and is given in Appendix E. The MATLAB program incorporates root locus, frequency response and transient response design methods [23].

The response characteristics for the uncompensated and compensated systems are given in Figure 6.6.3.5 for a ramp input and Figure 6.6.3.6 for a parabolic input. In addition, the actual position and velocity inputs for both the compensated and uncompensated system are given in Figure 6.6.3.7 and Figure 6.6.3.8 respectively. The uncompensated SIMULINK model is the same as the SIMULINK model for the compensated system as shown in Figure 6.6.3.3 with the exception that the PID compensators are removed. The response for the uncompensated system corresponds fairly well to the given input although for the ramp and parabolic inputs the steady state

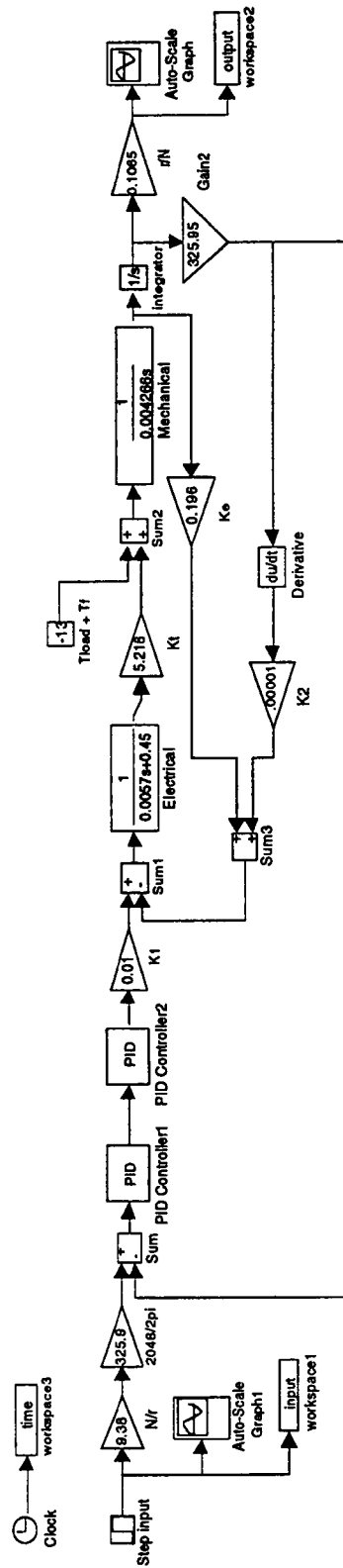


Figure 6.6.3.3 SIMULINK Model of the Controller with PI Compensators

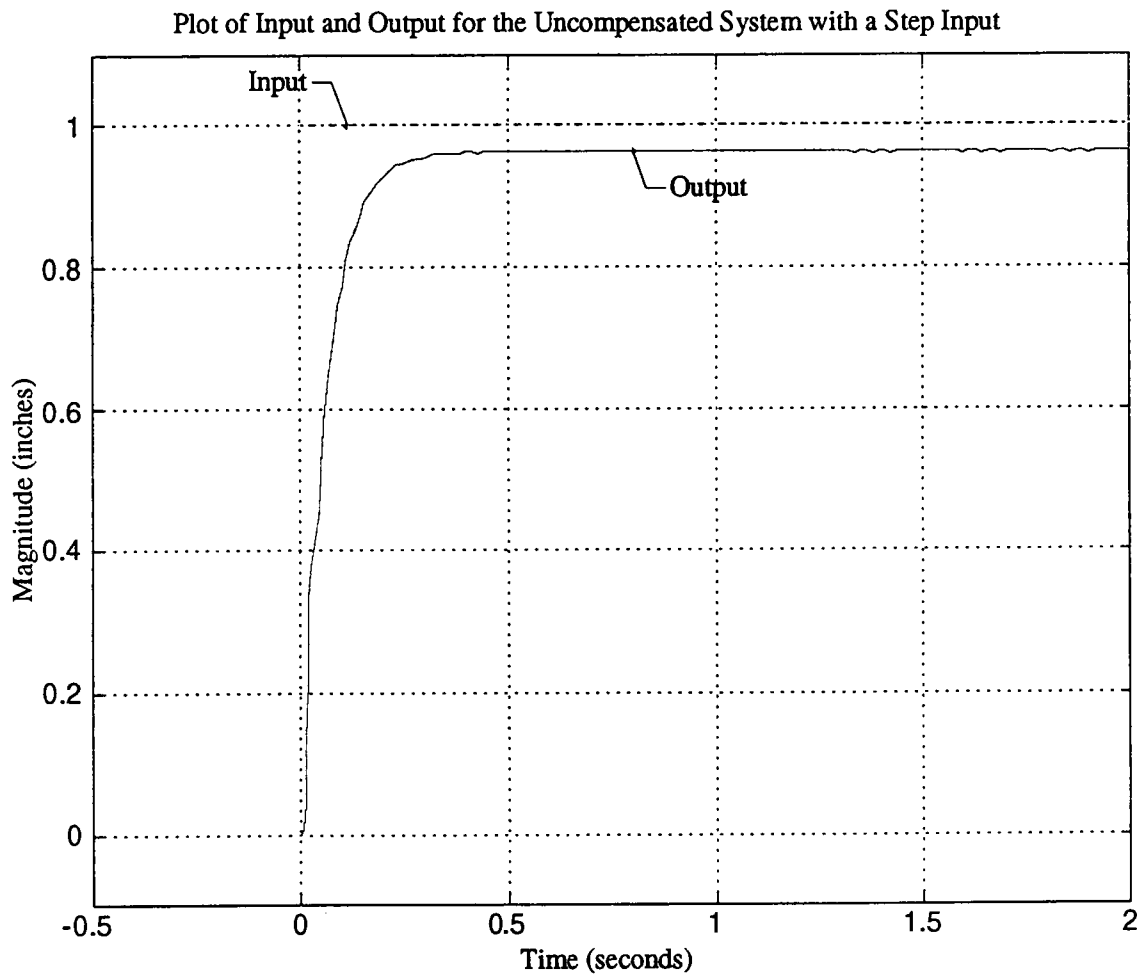


Figure 6.6.3.4 Input and Output of the Uncompensated System for a Step Input with $K_1 = 0.01$ and $K_2 = 0.00001$

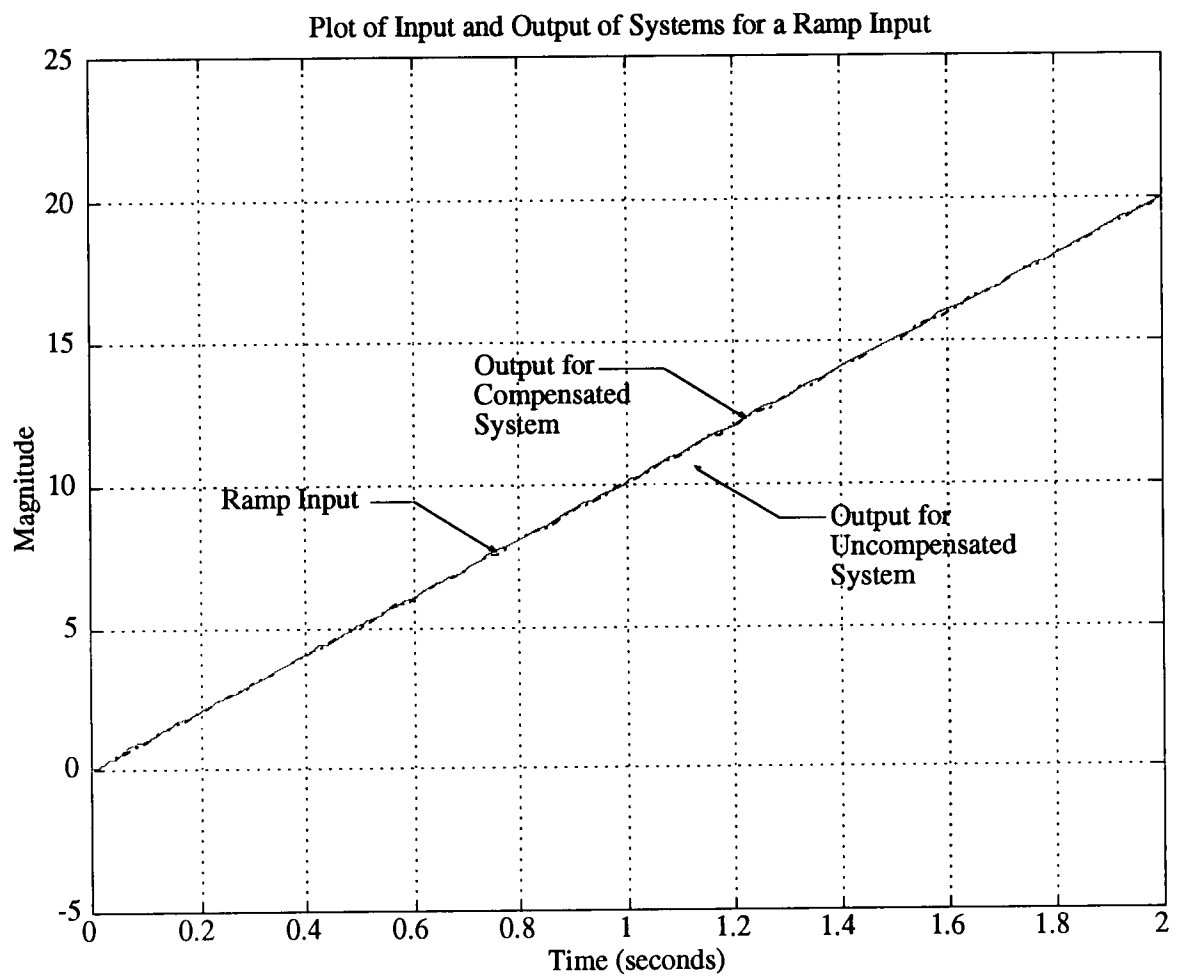


Figure 6.6.3.5 Plot of Input and Output of Compensated and Uncompensated System for a Ramp Input

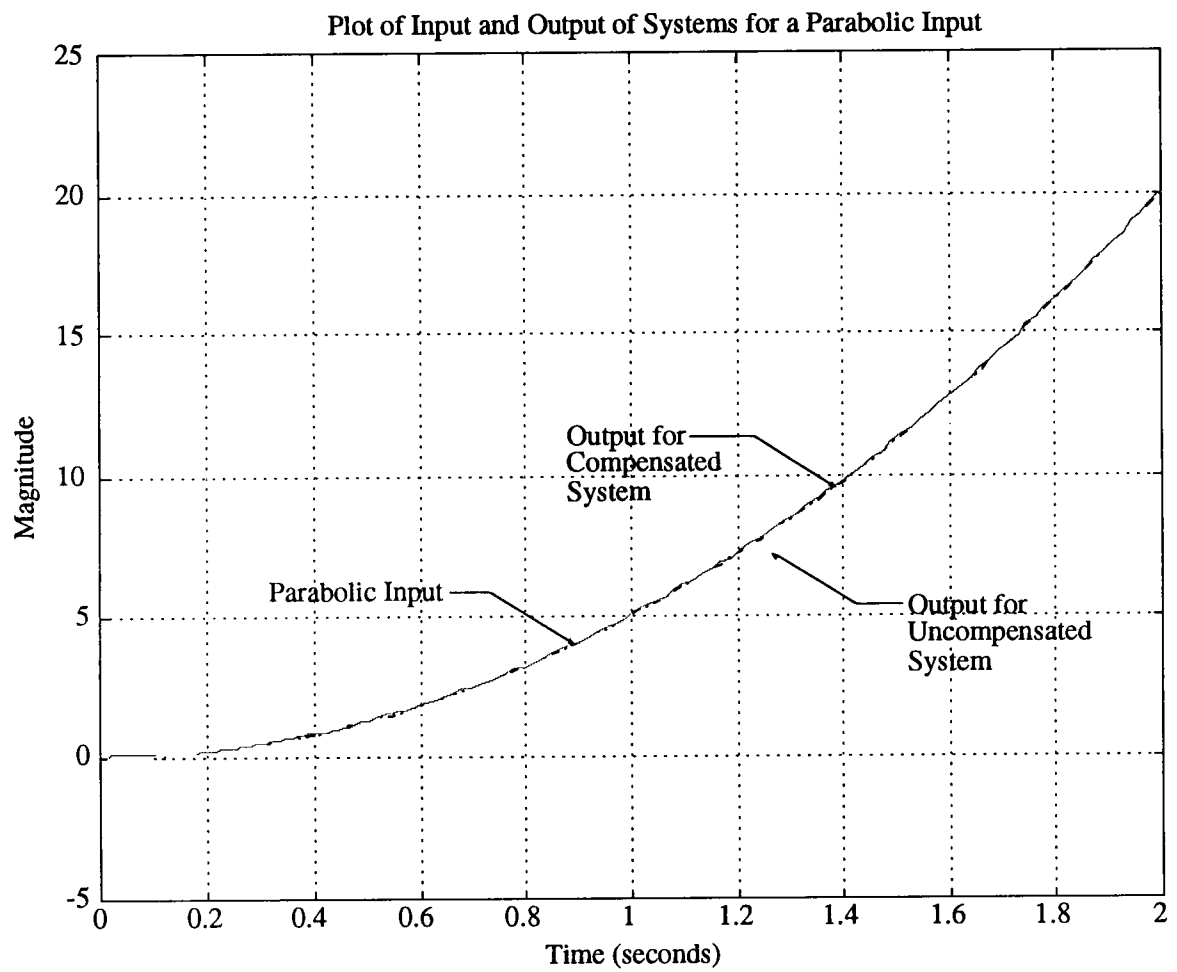


Figure 6.6.3.6 Plot of Input and Output of Compensated and Uncompensated System for a Parabolic Input

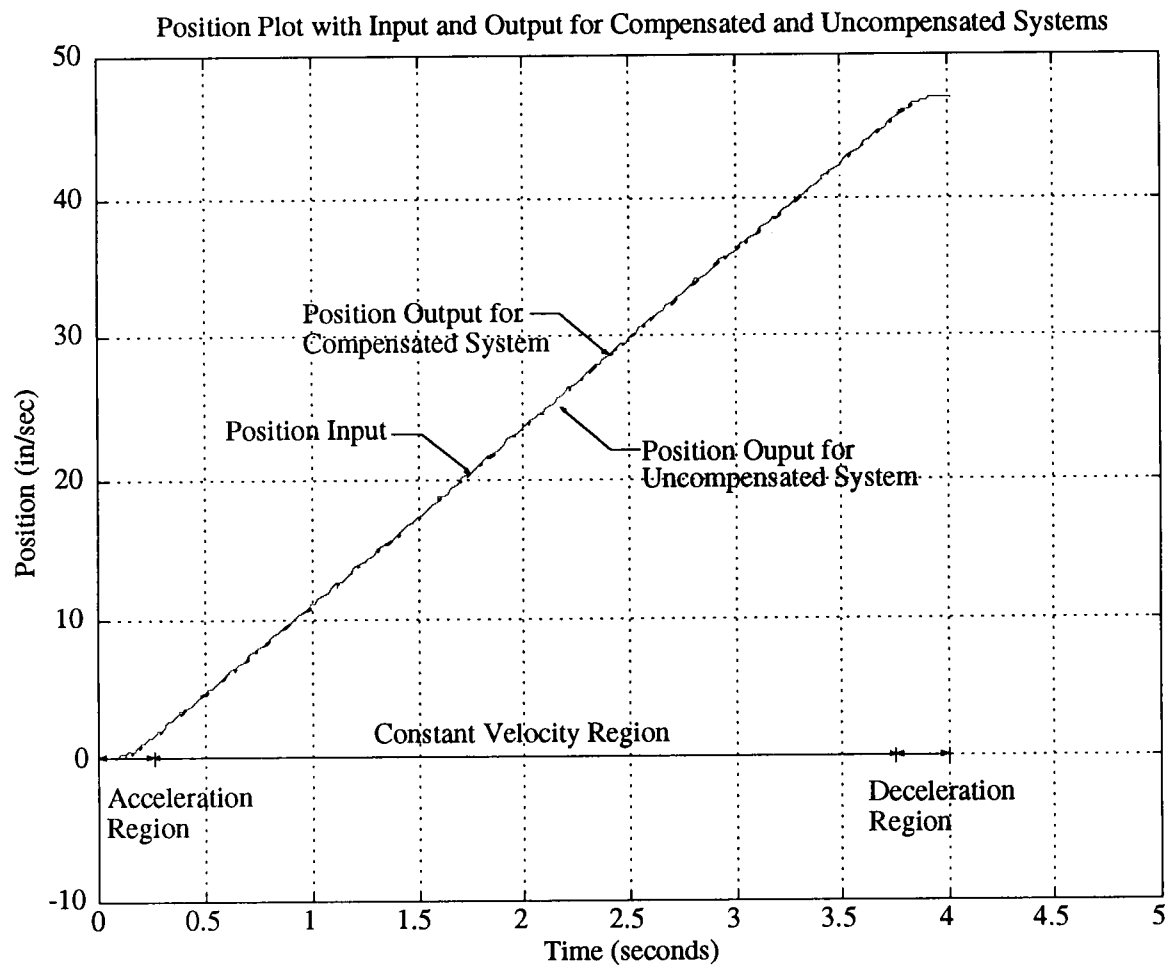


Figure 6.6.3.7 Position Plot with Input and Output for the Compensated and Uncompensated Systems

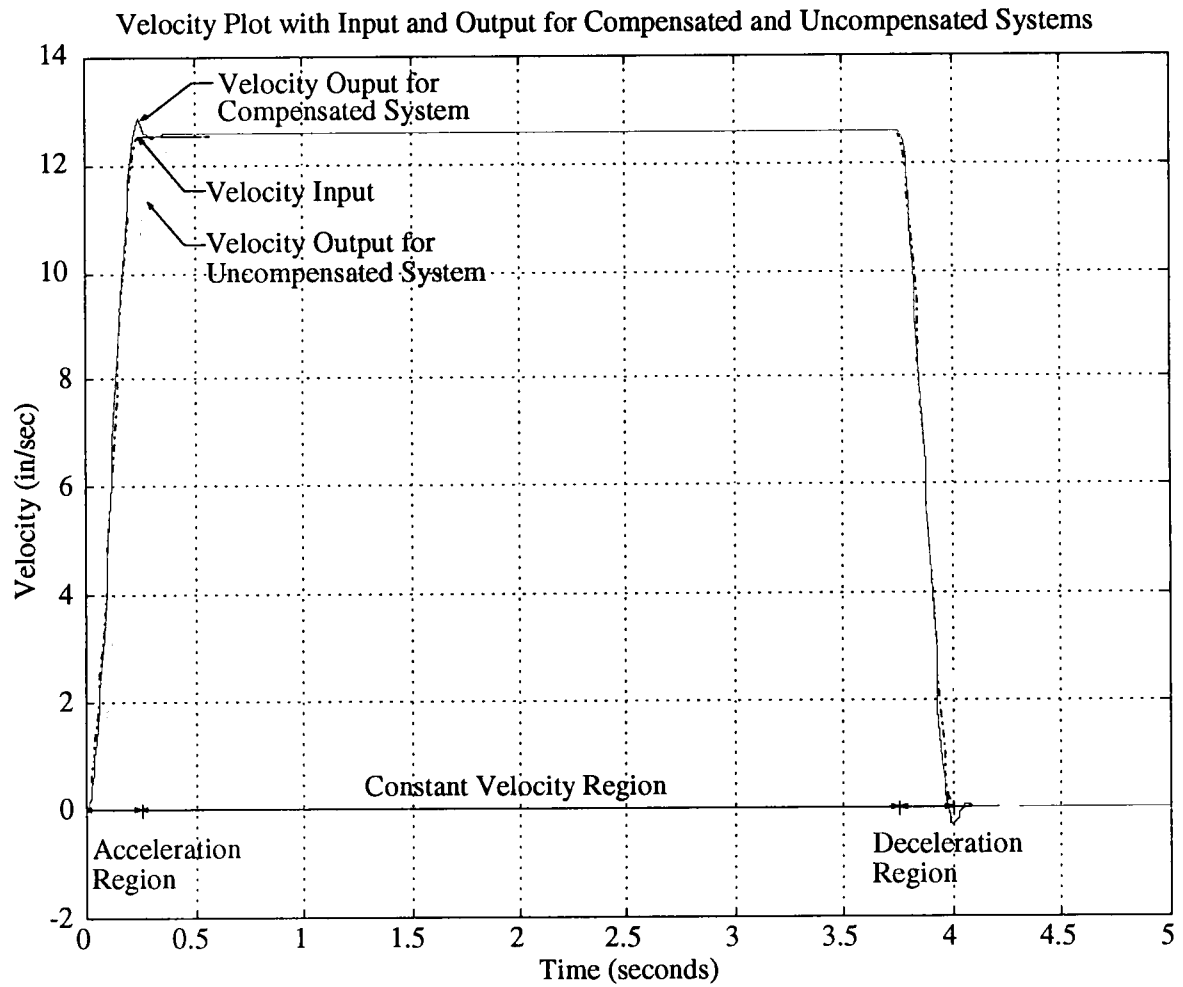


Figure 6.6.3.8 Velocity Plot with Input and Output for the Compensated and Uncompensated Systems

error approaches infinity although the output diverges at a very small rate. The divergence of the output from the input can be seen more easily in the parabolic response for the uncompensated system.

Since the goal of the project is to maximize the performance of the inspection station, the compensators are added to the system to reduce the steady state error of the system. The addition of compensators coincides with the conservative design approach taken to maximize the robustness and performance of the system.

When the PI controllers are implemented, the K_p and K_i gain constants for each of the PI compensators are set by evaluating the time response of the ramp, parabolic and actual position and velocity inputs. The gain values of the PI compensators were determined by systematic trial and error methods. For the first PI controller, K_p was found to be 3.5 and K_i was found to be 200. For the second controller, K_p was found to be 1.0 and K_i was found to be 1.0. With these compensator gain values, the ramp and parabolic responses of the system were plotted in Figure 6.6.3.5 for the ramp and Figure 6.6.3.6 for the parabolic input. The actual position and velocity inputs that will achieve the desired motion profile were shown in Figure 6.6.3.7 for the position input and Figure 6.6.3.8 for the velocity input. Both the position and velocity inputs are ramp and parabolic inputs pieced together in such a manner to achieve the desired motion profile.

The SIMULINK models for the position and velocity inputs are given in Appendix F along with the MATLAB programs used to generate the data points for the desired motion profile. These models allow for testing of the system, both compensated and uncompensated. The simulation capability allowed for the compensators to be tuned to achieve the performance characteristics suitable to the application, which for this case required smooth and precise position and velocity control.

6.6.3.1 Analysis and Simulation Results

The analysis and simulation of the motion controller allowed for the gain constants and compensators of the system to be determined. Originally, the system was determined to be a type 0 system, but two PI compensators were implemented to make the system a type 2 system which gave suitable transient responses for the inputs that the system will encounter. The gain values of the original system and compensators that were determined through analysis and simulation are given in Table 6.6.3.1.1. The gain values will be implemented into the controller in conjunction with the double PI control law to provide the desired transient response of the slider.

Table 6.6.3.1.1 Control System Gain Constants

Item	Gain Variable	Gain Value
Amplifier ₁	K_1	0.01
Amplifier ₂	K_2	0.00001
PI Controller ₁	K_{p1}	3.5
PI Controller ₁	K_{i1}	200.00
PI Controller ₂	K_{p2}	1.0
PI Controller ₂	K_{i2}	1.0

6.7 The Detailed Design

The culmination of the preliminary and detailed design efforts is the final detailed design. After several revisions of the design to account for budget consideration and changes in the BUPS and plant layout of the GSB Corbin, Ky., manufacturing facility, the final detailed design is shown in Figures 6.7.1, 6.7.2, 6.7.3, 6.7.4 and 6.7.5. This

design is the result of several iterations of design work and is in accordance with the specification and requirements outlined in Chapter 4 (System Design Requirements).

6.7.1 Assembly of the Inspection Station

The assembly of the inspection station is split into two phases. The first phase is for laboratory setup which will allow for system integration and testing. The second phase is integration of the inspection station into the GSB Corbin, Ky., brick manufacturing facility. When assembling the inspection station, special care should be given to proper installation of the vertical HLE100A linear actuators such that they are parallel so no binding occurs. The frame of the inspection station is comprised on ParFrame components which will be cut to the required dimensions. When constructing the frame, consult the mechanical drawings for location of the various members. Assembly of the ParFrame components shall be accomplished with ParFrame bracketry that has been specified in the mechanical drawings.

6.7.2 Integration of the Inspection Station

Like the assembly of the inspection station, the integration of the inspection station is also accomplished in phases. Integration of the OCS controller, servo controller and servo will be the first step in the integration process. Next, the frame shall be constructed, and all required in-house parts shall be machined. Once the frame is ready, the linear actuators shall be mounted and the servo motor attached. At this point in the integration process, testing of the control system shall be performed to verify that the slider follows the commanded motion profile while not overrunning the limit switches. After the controller has been implemented and is working properly, the other linear actuator shall be linked to

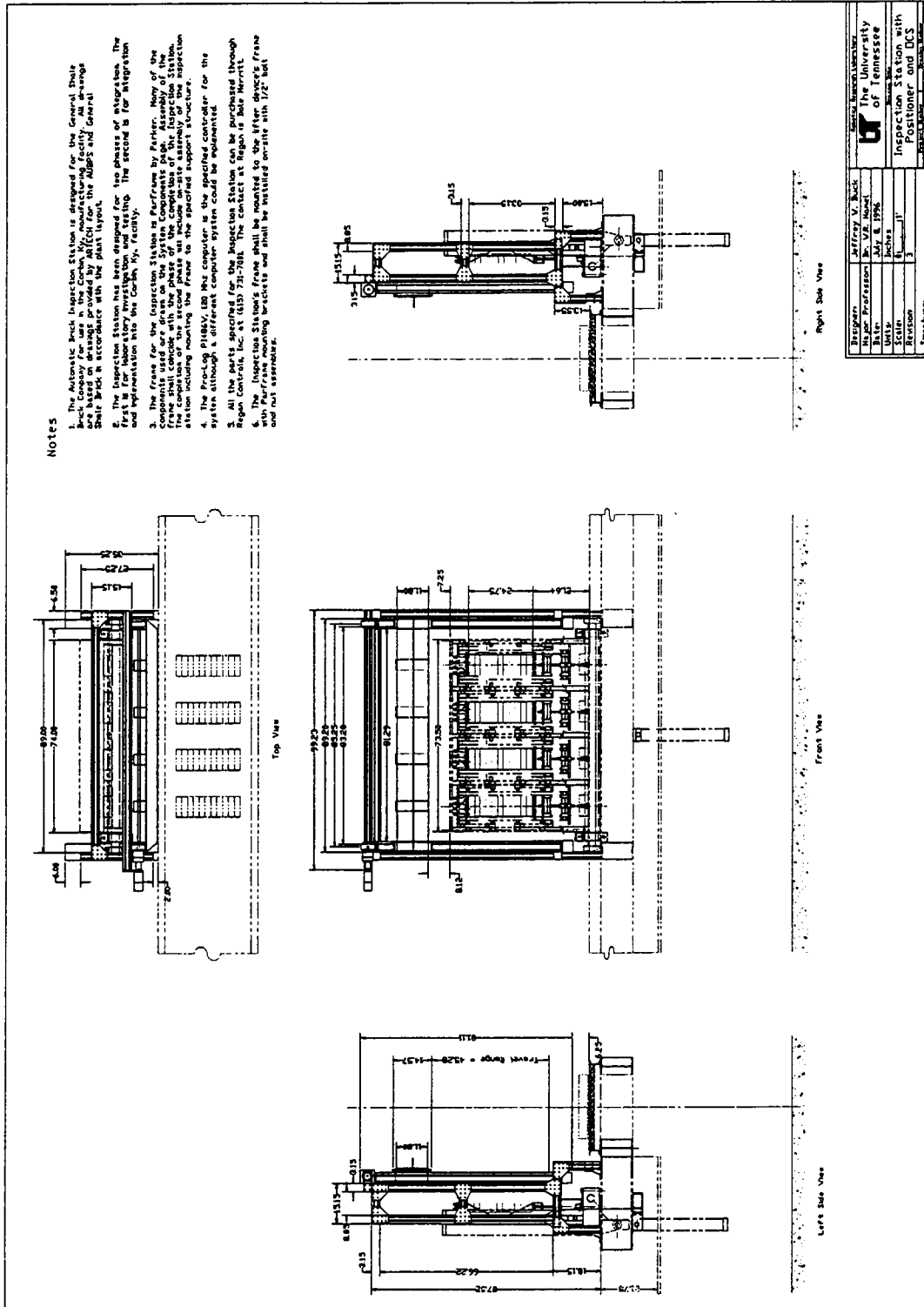


Figure 6.7.2 The Inspection Station with the Positioner Device and OCS

1. This drawing shows the Inspection Station in Phase 1 of its completion. Phase 1 is for observing function and migration of the Inspection Station.
2. The Operator Control Station shall be stationed close to the Inspection Station. The Operator Control Station is placed on the location of the DCS and center-entr for Phase 1.
3. A set of brack shall be placed in the spotting inspection position for the Phase 1 of the project. The brack shall be manually placed into the inspection position and shall be supported by the specified Airframe support structure.
4. A Serial core should be given to proper assembly of the frame components such that the linear actuators are parallel and no bending occurs when the frame is actuated.
5. The Inspection Station Frame is aimed to be the remainder of the top and bottom section of the frame. The top and bottom frame assembly is defined as the frame found below the center of the brack set being respected. The bottom frame assembly is the frame found below the center of the brack set being respected.

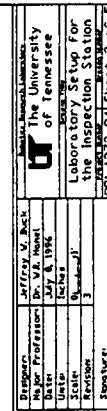


Figure 6.7.3 The Inspection Station in Laboratory Setup Configuration



the motor by the link shaft, and the carriage bar shall be attached. Once the load is attached to the motor, the controller shall be finely tuned to obtain the desired response for a given input profile. Now, the mechanical integration is complete and the integration and testing of the image analysis system begins. The integration of the image analysis system shall be performed by both the MAES and EE group.

6.7.3 Maintenance of the Inspection Station

The inspection station has been designed to minimize the maintenance required by GSB. Periodical lubrication of the sliding parts of the linear actuators is the only preventative maintenance required.

6.8 The Detailed Design Cost Estimate

In Table 6.8.1, the budget for the detailed design is given by Regan Control based on manufacturers prices. The price list given in Table 6.8.1 is subject to change, and the quotation value for the ParFrame components is an approximated value. The cost estimate includes all major components of the inspection station design with the exception of the laser scanners, laser scanner controller and labor for machining and assembly of the inspection station.

6.9 Bill of Materials for the Inspection Station

In Table 6.9.1, the complete bill of materials for the inspection station is given including all the hardware and supporting equipment to complete the positioner and controller of the inspection station. The bill of materials list all hardware to be procured and parts to be machined that will complete Phase I of the inspection station. As a supplement to Table 6.9.1, a reference chart is given in Table 6.9.2 to list all the ParFrame components which require special machining instructions. The two tables list all the

hardware equipment and parts to be machined with a description of the item and any special instructions that might be needed.

Table 6.8.1 Cost Estimate for Procured Hardware

Item	Quantity	Description	Price	Amount
1	1	Parker Hauser XY Gantry System to include double HLE100A w/85.25" center to center separation, cover profile system with standard carriage, link shaft, limit home switches, overrun proximity sensors, planetary gearbox PL90 N10, and cable carrier (See Mechanical Drawings)	\$9,500.00	\$9,500.00
2	1	Yaskawa SGM-08 Brushless Servo Motor w/ incremental encoder and 24 VDC brake	\$989.00	\$989.00
3	1	Yaskawa SGDA-08A Servo Drive	\$1,324.00	\$1,324.00
4	1	Yaskawa DE9404859 1m IO cable	\$97.00	\$97.00
5	1	Yaskawa DP9320081-2 5motor cable w/ brake	\$106.00	\$106.00
6	1	Yaskawa DP9320089-2 5m encoder cable	\$156.00	\$156.00
7	1	Yaskawa JUSP-OPO3A programmer	\$156.00	\$156.00
8	1	Optimised Control NM/2 ISA bus servo controller	\$1,900.00	\$1,900.00
9	1	Optimised NM/C/100 1m cable	\$155.00	\$155.00
10	1	Optimized NM/B6 Breakout Board	\$330.00	\$330.00
11	1	Optimized Cterm Programming System	NC	NC
12	1	Pro-Log computer PI486V, 120 MHz, 512 KB cache, 760- 15-250A industrial chassis, 1.44 MB 3.5" floppy drive, HD-002 1.2 GB IDE hard drive, spill resistant keyboard.	\$6,457.00	\$6,457.00
13	1	Xycom HMI 9450-SSW SoftScreen Workstation with touchscreen options	\$5950.00	\$5950.00
14	1	ParFrame Frame Components	\$3,000.00	\$3,000.00
Total				\$30,120.00

Table 6.9.1 Bill of Materials for the Inspection Station

Item	Unit Qty.	Part Number	Description
1	1	L10 Y 1150 DL 21 S S	Hauser HLE100A Actuator with Cover Profile System (Left Side)
2	1	L10 Y 1150 LS 21 S S	Hauser HLE100A Actuator with Cover Profile System (Right Side)
3	1	PL90 N10	Hauser Planetary Gearbox with Reduction Ratio of 10
4	1	LA10 2165 XX 0	Hauser Link Shaft for use with Double HLE Units
5	1	100-905900	Hauser Cable Carrier and Trough
6	2	See Catalog	Hauser Mechanical End Switch (NPN)
7	1	See Catalog	Hauser Proximity Switch (NPN)
8	1	See Catalog	Hauser Tripping Plate for Activation of Sensors
9	1	SGDA-08A	Yaskawa Servo Drive and Amplifier
10	1	SGM-08	Yaskawa Servo Motor SGM-08 with Incremental Encoder and Brake
11	1	RD1-1372-84:1	Scanner Carriage Bar to be Machined Inhouse
12	4	RD1-1372-84:2	Scanner Enclosure Modules to be Machined Inhouse
13	1	RD1-1372-84:3	Motor Mounting Plate with 1" through hole to be Machined Inhouse
14	1	RD1-1372-84:4	Motor Mounting Plate with 2.875" hole to be Machined Inhouse
15	1	PI486DX-120V	DCS: Prolog PI486V, 120Mhz PCI Industrial Computer
16	1	9450-SSW	DCS: Xycon Monitor (Softscreen Workstation)
17	1	CCC606062	Hoffman Enclosure for the DCS (600mmx600mmx600mm)
18	1	See REFERENCE Table	Inspection Station Frame: ParFrame Components
19	901.18'	ESH8080 (REF)	ParFrame ESH8080 Aluminum Extrusion for Body of Frame
20	96	ESF5022	ParFrame Anchor Fastening Assembly
21	100	ESF8231	ParFrame Drop in T-Nut
22	400	ESF8031A	Economy T-Nut (5/16 - 18)
23	6	ESG4040	ParFrame ESG4040 Gusset for Frame Connections
24	8	ESG8040	ParFrame ESG8040 Gussets for Frame Connections
25	14	ESJ8010	ParFrame ESJ8010 Frame Right Angle Connector
26	12	ESJ8012	ParFrame ESJ8012 Frame 'T' Connector
27	9	ESC8080	ParFrame End Caps for ESH8080 Profile
28	36	ESA0048	ParFrame Push-In Fastener
29	8	ESA8010	ParFrame Floor Mounting Brackets
30	460	ESF9031-063	ParFrame Button Head Socket Cap Screws (5/16-18 x 5/8")
31	40	ESF9031-075	ParFrame Button Head Cap Screws (5/16-18 x 3/4")
32	500	ESF6131	ParFrame Lock Washer
33	16	ESB4080	ParFrame Angle Brackets for Attaching Actuators to the Frame
34	6	ESJ8002	ParFrame Straight Connector

Table 6.9.2 Reference Chart for ParFrame Components

Item	Quantity	Part Number	Service Part Number	Description
1	4	ESH8080	ESE8080 x 15.00'ESE1040-A	Bottom Assembly of Frame: 15.00' in Length (each)
2	2	ESH8080	ESE8080 x 15.15'	Top Assembly of Frame: 15.15' in Length (each)
3	4	ESH8080	ESE8080 x 8.85' ESE0002-A1-A2-A5-A6-B1-B2-B5-B6	Top Assembly of Frame: 8.85' in Length (each)
4	4	ESH8080	ESE8080 x 66.22'	Top Assembly of Frame : 66.22' in Length (each)
5	2	ESH8080	ESE8080 x 27.25'	Bottom Assembly of Frame: 27.25' in Length (each)
6	4	ESH8080	ESE8080 x 89.20' ESE0002-A1-A2-A5-A6-B1-B2-B5-B6	Top/Bottom Assembly of Frame: 89.20' in Length (each)
7	1	ESH8080	ESE8080 x 99.23'ESE1040-A	Top Assembly of Frame: 99.25' in Length

Chapter Seven

Conclusion

7.1 Summary

The design and development of the inspection station as presented in this thesis is the culmination of two years of research for the General Shale Brick company. The mechanical and controller design of the inspection station has been completed and is ready for procurement and assembly. The completion of the detailed design has lead to the generation of AutoCAD drawings and hardware cost estimates with integration and assembly instructions. Once the inspection station positioner and controller are assembled and properly integrated, the image analysis algorithms can be implemented to complete the inspection station.

In order to complete the design for the automated inspection station, a feasibility study has been performed, the system design requirements defined, alternative conceptual designs generated and preliminary and detailed design completed. These functions were performed by systematically progressing through the design until the final design was completed. The design was an iterative process where every old revision pointed the way to a better and more complete solution. A wide range of topics where investigated in order to achieve the final design and verify its feasibility. Topics such as load distributions, beam deflections, motion profiles, system modeling, control laws, control system simulation, component selection and development of a detailed design using a CAD software package were all undertaken in order to complete this design. By investigating the design from all aspects that were relative to the design and working with product manufacturers and distributors, the design is complete and accurate with system components that best fit the application.

7.2 Future Research

An immediate research topic for the completion of the inspection station is the further development of the image analysis technique and computer algorithms. Only after the image analysis hardware and control algorithms can be implemented, can the inspection station be used for the inspection of brick. Therefore, testing and implementation of the image analysis system is key.

In addition, further research may explore the possibility of a more optimized system controller which would focus on the total integration of the system. The total integration would include the image analysis system, the positioner system and the operator interface system. Depending of the computational requirements of the image analysis system, it might be best to have the image analysis controller separate from the main controller, or it might be best to combine the controllers into one integrated controller.

Future research areas include applications where robots can be integrated into the brick manufacturing facilities as well as other types of industries. For the brick industry, robots could be implemented into the manufacturing process in the near term to perform task such as brick setting, restacking of brick on broken bungs due to skewed or fallen brick, and dehacking of brick. The application of robotics for such tasks is realizable with research. An example of research that would be useful for the restacking of broken bungs is the incorporation of sensory devices on the gripper so that the robot could detect the edges of the brick. By knowing the position and orientation of the edges of the brick, the robot could pick up the brick and rebuild the bung to its desired state. This same approach could be implemented for the dehacking process such that the robotic dehacker could successfully pick up misplaced brick by sensing its actual location versus its defined position. This type of robustness would make robotics an feasible solution to many of the task performed in the production of brick without many of the restrictions found in classical automation solutions.

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Appendices

Appendix A. Demonstration AML Program

```

--*****
--*****
--      General Shale Demo Project
--      Programmer:  Jeffrey W. Buck
--      Program:  Demo.aml
--      Date:  December 14,1994
--      Application Number 1 on IBM controller panel
--*****
--*****
--      The aml (A Manufacturing Language) language is used in
--      conjunction with IBM robots.  This program was developed
--      in conjunction with the feasibility study performed for
--      the investigation of robotic dehacking.  The IBM 7547
--      robot was used in the study and this aml program controls
--      the structure of the demonstration.  The pick and place
--      instructions for the aml language use (x,y,z, and roll)
--      components will x,y,z components given in the units of
--      millimeters and roll given in angular degrees.
--*****
--*****
--      Define Some Common Points
PRE:NEW PT(460,385,0,0);          -- START POINT OF WORK SPACE
CON:NEW PT(-735,500,0,0);       -- CONVEYOR SET DOWN POINT
CAR:NEW PT(-735,500,0,-90);     -- SET DOWN POINT FOR 2ND COARSE
ROL:NEW PT(-735,500,-140,-90):  -- RELEASE POINT
--*****
--      SUBROUTINE SECTION
MAIN: SUBR;
OPENGR: SUBR;                  -- OPEN PNEUMATIC GRIPPER
      RELEASE;                 -- COMMAND TO OPEN GRIPPER
      DELAY(.1);               -- A DELAY OF 0.1 SECONDS
END;
--
CLOSEGR: SUBR;                 -- CLOSE PNEUMATIC GRIPPER
      GRASP;                   -- COMMAND TO CLOSE GRIPPER
      DELAY(0.3);              -- A DELAY OF 0.3 SECONDS
END;
--
SET_DOWN: SUBR;                -- SUBROUTINE TO PLACE BRICKS ON
                                -- CONVEYOR
      WRITEO(6,0);             -- TURN CONVEYOR OFF USING PORT 6
      PMOVE(ROL);              -- PERFORM MOVE (ROL)
      OPENGR;                  -- SUB. OPENGR
      ZMOVE(-55);              -- MOVE Z-AXIS TO THE  -55 mm POINT
      CLOSEGR;                 -- SUB. CLOSEGR
      ZMOVE(-35);              -- MOVE Z-AXIS TO THE -35 mm POINT
      WRITEO(6,1);             -- TURN CONVEYOR ON
      DELAY(0.8);              -- DELAY FOR 0.8 SECONDS
      WRITEO(6,0);             -- TURN CONVEYOR OFF
      PMOVE(ROL);              -- RETURN TO RELEASE POINT
      OPENGR;                  -- SUB. OPENGR
      ZMOVE (0);               -- MOVE Z-AXIS TO THE 0 POINT
      WRITE(6,1);              -- TURN CONVEYOR ON
END;

```

```

--
-- BRICK SET NUMBER 1 (4 BRICKS ON TOP COARSE ON SAMPLE PALLET)
SET_1: SUBR;
    PMOVE(PT(-377,500,0,0)); -- MOVE TO START POINT
    PMOVE(PT(-377,885,0,0)); -- POINT NUMBER 1
    ZMOVE(-25); -- MOVE DOWN TO GRASP BRICK
    CLOSEGR; -- GRASP THE BRICK
    ZMOVE(0); -- LIFT THE BRICK
    PMOVE(CON); -- MOVE BRICKS TO SET DOWN POINT
    SET_DOWN; -- SUBROUTINE TO SET DOWN THE BRICK
END;
--
-- BRICK SET NUMBER 2 (4 BRICKS ON TOP COARSE ON SAMPLE PALLET)
SET_2: SUBR;
    PMOVE(PT(-195,500,0,0)); -- MOVE TO START POINT
    PMOVE(PT(-195,885,0,0)); -- POINT NUMBER 2
    ZMOVE(-25); -- MOVE DOWN TO GRASP BRICK
    CLOSEGR; -- GRASP THE BRICK
    ZMOVE(0); -- LIFT THE BRICK
    PMOVE(PT(-195,500,0,0)); -- MOVE TO START POINT
    PMOVE(CON); -- MOVE BRICKS TO SET DOWN POINT
    SET_DOWN; -- SUBROUTINE TO SET DOWN THE BRICK
END;
--
-- BRICK SET NUMBER 3 (6 BRICKS ON TOP COARSE ON SAMPLE PALLET)
SET_3: SUBR;
    PMOVE(PT(-32,500,0,0)); -- MOVE TO START POINT
    PMOVE(PT(-32,885,0,0)); -- POINT NUMBER 3
    ZMOVE(-25); -- MOVE DOWN TO GRASP BRICK
    CLOSEGR; -- GRASP THE BRICK
    ZMOVE(0); -- LIFT THE BRICK
    PMOVE(PT(-32,500,0,0)); -- MOVE TO START POINT
    PMOVE(CON); -- MOVE BRICKS TO SET DOWN POINT
    SET_DOWN; -- SUBROUTINE TO SET DOWN THE BRICK
END;
--
-- BRICK SET NUMBER 4 (4 BRICKS ON TOP COARSE ON SAMPLE PALLET)
SET_4: SUBR;
    PMOVE(PT(135,500,0,0)); -- MOVE TO START POINT
    PMOVE(PT(135,885,0,0)); -- POINT NUMBER 4
    ZMOVE(-25); -- MOVE DOWN TO GRASP BRICK
    CLOSEGR; -- GRASP THE BRICK
    ZMOVE(0); -- LIFT THE BRICK
    PMOVE(CON); -- MOVE BRICKS TO SET DOWN POINT
    SET_DOWN; -- SUBROUTINE TO SET DOWN THE BRICK
END;
--
-- BRICK SET NUMBER 5 (4 BRICKS ON TOP COARSE ON SAMPLE PALLET)
SET_5: SUBR;
    PMOVE(PT(311,500,0,0)); -- MOVE TO START POINT
    PMOVE(PT(311,885,0,0)); -- POINT NUMBER 5
    ZMOVE(-25); -- MOVE DOWN TO GRASP BRICK
    CLOSEGR; -- GRASP THE BRICK
    ZMOVE(0); -- LIFT THE BRICK
    PMOVE(CON); -- MOVE BRICKS TO SET DOWN POINT
    SET_DOWN; -- SUBROUTINE TO SET DOWN THE BRICK
END;

```

```

--
--BRICK SET NUMBER 6 (4 BRICKS ON SECOND COARSE ON SAMPLE PALLET)
SET_6: SUBR;
    PMOVE(PT(-338,410,0,-90));    -- MOVE TO START POINT #6
    ZMOVE(-206);                  -- MOVE DOWN TO GRASP BRICK
    CLOSEGR;                       -- GRASP THE BRICK
    PMOVE(PT(-342,410,0,-90));    -- GIVE 4 mm CLEARANCE FOR BRICK
                                   -- THE 4 mm CLEARANCE IS
                                   -- ATTRIBUTED TO THE
                                   -- BETWEEN BRICKS
INTERACTION                        -- CONTACT
IN SLIDING                         --
    PMOVE(CAR);                   -- MOVE BRICKS TO SET DOWN POINT
    SET_DOWN;                     -- SUBROUTINE TO SET DOWN THE BRICK
END;
--
--BRICK SET NUMBER 7 (6 BRICKS ON SECOND COARSE ON SAMPLE PALLET)
SET_7: SUBR;
    PMOVE(PT(-338,593,0,-90));    -- MOVE TO START POINT #7
    ZMOVE(-206);                  -- MOVE DOWN TO GRASP BRICK
    CLOSEGR;                       -- GRASP THE BRICK
    PMOVE(PT(-342,593,0,-90));    -- GIVE 4 mm CLEARANCE FOR BRICK
    PMOVE(CAR);                   -- MOVE BRICKS TO SET DOWN POINT
    SET_DOWN;                     -- SUBROUTINE TO SET DOWN THE BRICK
END;
--
--BRICK SET NUMBER 8 (4 BRICKS ON SECOND COARSE ON SAMPLE PALLET)
SET_8: SUBR;
    PMOVE(PT(-338,755,0,-90));    -- MOVE TO START POINT #8
    ZMOVE(-206);                  -- MOVE DOWN TO GRASP BRICK
    CLOSEGR;                       -- GRASP THE BRICK
    PMOVE(PT(-342,755,0,-90));    -- GIVE 4 mm CLEARANCE FOR BRICK
    PMOVE(CAR);                   -- MOVE BRICKS TO SET DOWN POINT
    SET_DOWN;                     -- SUBROUTINE TO SET DOWN THE BRICK
END;
--
--BRICK SET NUMBER 9 (4 BRICKS ON SECOND COARSE ON SAMPLE PALLET)
SET_9: SUBR;
    PMOVE(PT(-338,935,0,-90));    -- MOVE TO START POINT #9
    ZMOVE(-206);                  -- MOVE DOWN TO GRASP BRICK
    CLOSEGR;                       -- GRASP THE BRICK
    PMOVE(PT(-342,935,0,-90));    -- GIVE 4 mm CLEARANCE FOR BRICK
    PMOVE(CAR);                   -- MOVE BRICKS TO SET DOWN POINT
    SET_DOWN;                     -- SUBROUTINE TO SET DOWN THE BRICK
END;
--
-- BRICK SET NUMBER 10 (4 BRICKS ON SECOND COARSE ON SAMPLE
-- PALLET)
SET_10: SUBR;
    PMOVE(PT(-135,410,0,-90));    -- MOVE TO START POINT #10
    ZMOVE(-206);                  -- MOVE DOWN TO GRASP BRICK
    CLOSEGR;                       -- GRASP THE BRICK
    PMOVE(PT(-139,410,0,-90));    -- GIVE 4 mm CLEARANCE FOR BRICK
    PMOVE(CAR);                   -- MOVE BRICKS TO SET DOWN POINT
    SET_DOWN;                     -- SUBROUTINE TO SET DOWN THE BRICK
END;
--
-- BRICK SET NUMBER 11 (6 BRICKS ON SECOND COARSE ON SAMPLE

```

```

-- PALLET)
SET_11: SUBR;
    PMOVE(PT(-135,593,0,-90));    -- MOVE TO START POINT #11
    ZMOVE(-206);                  -- MOVE DOWN TO GRASP BRICK
    CLOSEGR;                       -- GRASP THE BRICK
    PMOVE(PT(-139,593,0,-90));    -- GIVE 4 mm CLEARANCE FOR BRICK
    PMOVE(CAR);                    -- MOVE BRICKS TO SET DOWN POINT
    SET_DOWN;                      -- SUBROUTINE TO SET DOWN THE BRICK
END;
--
-- BRICK SET NUMBER 12 (4 BRICKS ON SECOND COARSE ON SAMPLE
-- PALLET)
SET_12: SUBR;
    PMOVE(PT(-135,755,0,-90));    -- MOVE TO START POINT #12
    ZMOVE(-206);                  -- MOVE DOWN TO GRASP BRICK
    CLOSEGR;                       -- GRASP THE BRICK
    PMOVE(PT(-139,755,0,-90));    -- GIVE 4 mm CLEARANCE FOR BRICK
    PMOVE(CAR);                    -- MOVE BRICKS TO SET DOWN POINT
    SET_DOWN;                      -- SUBROUTINE TO SET DOWN THE BRICK
END;
--
-- BRICK SET NUMBER 13 (4 BRICKS ON SECOND COARSE ON SAMPLE
-- PALLET)
SET_13: SUBR;
    PMOVE(PT(-135,935,0,-90));    -- MOVE TO START POINT #13
    ZMOVE(-206);                  -- MOVE DOWN TO GRASP BRICK
    CLOSEGR;                       -- GRASP THE BRICK
    PMOVE(PT(-139,935,0,-90));    -- GIVE 4 mm CLEARANCE FOR BRICK
    PMOVE(CAR);                    -- MOVE BRICKS TO SET DOWN POINT
    SET_DOWN;                      -- SUBROUTINE TO SET DOWN THE BRICK
END;
--
-- BRICK SET NUMBER 14 (4 BRICKS ON SECOND COARSE ON SAMPLE
-- PALLET)
SET_14: SUBR;
    PMOVE(PT(68,410,0,-90));      -- MOVE TO START POINT #14
    ZMOVE(-206);                  -- MOVE DOWN TO GRASP BRICK
    CLOSEGR;                       -- GRASP THE BRICK
    PMOVE(PT(64,410,0,-90));      -- GIVE 4 mm CLEARANCE FOR BRICK
    PMOVE(CAR);                    -- MOVE BRICKS TO SET DOWN POINT
    SET_DOWN;                      -- SUBROUTINE TO SET DOWN THE BRICK
END;
--
-- BRICK SET NUMBER 15 (6 BRICKS ON SECOND COARSE ON SAMPLE
-- PALLET)
SET_15: SUBR;
    PMOVE(PT(68,593,0,-90));      -- MOVE TO START POINT #15
    ZMOVE(-206);                  -- MOVE DOWN TO GRASP BRICK
    CLOSEGR;                       -- GRASP THE BRICK
    PMOVE(PT(64,593,0,-90));      -- GIVE 4 mm CLEARANCE FOR BRICK
    PMOVE(CAR);                    -- MOVE BRICKS TO SET DOWN POINT
    SET_DOWN;                      -- SUBROUTINE TO SET DOWN THE BRICK
END;
--
-- BRICK SET NUMBER 16 (4 BRICKS ON SECOND COARSE ON SAMPLE
-- PALLET)
SET_16: SUBR;

```

```

        PMOVE(PT(68,755,0,-90));      -- MOVE TO START POINT #16
        ZMOVE(-206);                  -- MOVE DOWN TO GRASP BRICK
        CLOSEGR;                      -- GRASP THE BRICK
        PMOVE(PT(64,755,0,-90));      -- GIVE 4 mm CLEARANCE FOR BRICK
        PMOVE(CAR);                   -- MOVE BRICKS TO SET DOWN POINT
        SET_DOWN;                     -- SUBROUTINE TO SET DOWN THE BRICK
END;
--
-- BRICK SET NUMBER 17 (4 BRICKS ON SECOND COARSE ON SAMPLE
-- PALLET)
SET_17: SUBR;
        PMOVE(PT(68,935,0,-90));      -- MOVE TO START POINT #17
        ZMOVE(-206);                  -- MOVE DOWN TO GRASP BRICK
        CLOSEGR;                      -- GRASP THE BRICK
        PMOVE(PT(64,935,0,-90));      -- GIVE 4 mm CLEARANCE FOR BRICK
        PMOVE(CAR);                   -- MOVE BRICKS TO SET DOWN POINT
        SET_DOWN;                     -- SUBROUTINE TO SET DOWN THE BRICK
END;
--
-- BRICK SET NUMBER 18 (4 BRICKS ON SECOND COARSE ON SAMPLE
-- PALLET)
SET_18: SUBR;
        PMOVE(PT(271,410,0,-90));     -- MOVE TO START POINT #18
        ZMOVE(-206);                  -- MOVE DOWN TO GRASP BRICK
        CLOSEGR;                      -- GRASP THE BRICK
        ZMOVE(0);                     -- MOVE TO THE Z-AXIS 0 LOCATION
        PMOVE(CAR);                   -- MOVE BRICKS TO SET DOWN POINT
        SET_DOWN;                     -- SUBROUTINE TO SET DOWN THE BRICK
END;
--
-- BRICK SET NUMBER 19 (6 BRICKS ON SECOND COARSE ON SAMPLE
-- PALLET)
SET_19: SUBR;
        PMOVE(PT(271,593,0,-90));     -- MOVE TO START POINT #19
        ZMOVE(-206);                  -- MOVE DOWN TO GRASP BRICK
        CLOSEGR;                      -- GRASP THE BRICK
        ZMOVE(0);                     -- MOVE TO THE Z-AXIS 0 LOCATION
        PMOVE(CAR);                   -- MOVE BRICKS TO SET DOWN POINT
        SET_DOWN;                     -- SUBROUTINE TO SET DOWN THE BRICK
END;
--
-- BRICK SET NUMBER 20 (4 BRICKS ON SECOND COARSE ON SAMPLE
-- PALLET)
SET_20: SUBR;
        PMOVE(PT(271,755,0,-90));     -- MOVE TO START POINT #20
        ZMOVE(-206);                  -- MOVE DOWN TO GRASP BRICK
        CLOSEGR;                      -- GRASP THE BRICK
        ZMOVE(0);                     -- MOVE TO THE Z-AXIS 0 LOCATION
        PMOVE(CAR);                   -- MOVE BRICKS TO SET DOWN POINT
        SET_DOWN;                     -- SUBROUTINE TO SET DOWN THE BRICK
END;
--
-- BRICK SET NUMBER 21 (4 BRICKS ON SECOND COARSE ON SAMPLE
-- PALLET)
SET_21: SUBR;
        PMOVE(PT(271,935,0,-90));     -- MOVE TO START POINT #21
        ZMOVE(-206);                  -- MOVE DOWN TO GRASP BRICK

```

```

CLOSEGR;                -- GRASP THE BRICK
ZMOVE(0);               -- MOVE TO THE Z-AXIS 0 LOCATION
PMOVE(CAR);             -- MOVE BRICKS TO SET DOWN POINT
SET_DOWN;               -- SUBROUTINE TO SET DOWN THE BRICK
END;

--          END OF SUBROUTINE SECTION
--*****
--*****
--          BEGINNING OF COMMAND SEQUENCE
--*****
PAYLOAD(7);             -- PAYLOAD SPEED SETTING
CLOSEGR;                -- TEST GIPPER (CLOSE)
OPENGR;                 -- TEST GRIPPER (OPEN)
PMOVE(PRE);             -- MOVE TO WORKSPACE
LINEAR(25);             -- SET SYSTEM TO LINEAR MOTION
SET_3;                  -- DEHACK BRICK SET #3 FIRST
SET_2;                  -- DEHACK BRICK SET #2 NEXT
SET_1;                  -- DEHACK BRICK SET #1 NEXT
SET_4;                  -- DEHACK BRICK SET #4 NEXT
SET_5;                  -- DEHACK BRICK SET #5 NEXT
-- THE TOP LAYER OF THE SAMPLE PALLET HAS NOW BEEN DEHACKED
SET_7;                  -- DEHACK BRICK SET #7 NEXT
SET_6;                  -- DEHACK BRICK SET #6 NEXT
SET_8;                  -- DEHACK BRICK SET #8 NEXT
SET_9;                  -- DEHACK BRICK SET #9 NEXT
-- THE FIRST COLUMN OF THE SECOND COARSE HAS NOW BEEN DEHACKED
SET_11;                 -- DEHACK BRICK SET #11 NEXT
SET_10;                 -- DEHACK BRICK SET #10 NEXT
SET_12;                 -- DEHACK BRICK SET #12 NEXT
SET_13;                 -- DEHACK BRICK SET #13 NEXT
-- THE SECOND COLUMN OF THE SECOND COARSE HAS NOW BEEN
-- DEHACKED
SET_15;                 -- DEHACK BRICK SET #15 NEXT
SET_14;                 -- DEHACK BRICK SET #14 NEXT
SET_16;                 -- DEHACK BRICK SET #16 NEXT
SET_17;                 -- DEHACK BRICK SET #17 NEXT
-- THE THIRD COLUMN OF THE SECOND COARSE HAS NOW BEEN DEHACKED
SET_19;                 -- DEHACK BRICK SET #19 NEXT
SET_18;                 -- DEHACK BRICK SET #18 NEXT
SET_20;                 -- DEHACK BRICK SET #20 NEXT
SET_21;                 -- DEHACK BRICK SET #21 NEXT
-- THE FOURTH AND LAST COLUMN OF THE SECOND COARSE HAS NOW
-- BEEN DEHACKED
-- THE ENTIRE SAMPLE PALLER HAS NOW BEEN DEHACKED
PMOVE(PRE);             -- RETURN TO START POINT
WRITEO(6,0);            -- TURN OFF CONVEYOR BELT
END;                     -- END OF COMMAND PROGRAM
--*****
--          END OF DEMO PROGRAM TO DEHACK A SAMPLE BRICK BUNG
--*****

```

Appendix B. Calculation of the Motion Profiles

The following calculations show the formulation of the motion profile equations given in Chapter 5.

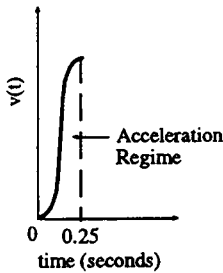
Requirements:

1. Time for Completion of Inspection Process = 10 seconds
2. Stroke length = 47 inches
3. Design for Worst Case (maximum acceleration)

Assumptions:

1. Acceleration Time = 0.25 seconds
2. Deceleration Time = 0.25 seconds
3. Constant Velocity Time = 3.5 seconds

First, analyze the acceleration regime to start the motion profile:



For the velocity profile shown, a third order polynomial will provide smooth motion for the velocity as well as the acceleration and position profiles. The third order polynomial looks like:

$$v(t) = a_3t^3 + a_2t^2 + a_1t + a_0.$$

By taking the derivative of this, the acceleration profile can be obtained in the form of:

$$a(t) = \frac{dv(t)}{dt} = 3a_3t^2 + 2a_2t + a_1.$$

Likewise by taking the integral of the velocity profile equation, the position profile can be obtained in the form of:

$$s(t) = \int v(t) dt = \frac{a_3t^4}{4} + \frac{a_2t^3}{3} + \frac{a_1t^2}{2} + a_0t + C.$$

Now by substitution of the initial and final conditions, the equation constants can be found as follows.

The initial conditions are: $t_0 = 0$ seconds, $t_f = 0.25$ seconds, $v(t_0) = 0$, $v(t_f) = \text{slew velocity}$, $a(t_0) = 0$ and $a(t_f) = 0$.

Therefore:

$$v(t_0) = a_3t_0^3 + a_2t_0^2 + a_1t_0 + a_0 = 0 \text{ which means that } a_0 = 0.$$

Now:

$$a(t_0) = 3a_3t_0^2 + 2a_2t_0 + a_1 = 0 \text{ which means that } a_1 = 0.$$

Therefore:

$$a_3 = -2.66667a_2.$$

And this reduces the velocity equation to:

$$v(t) = -2.66667a_2t^3 + a_2t^2 \text{ for } 0 < t < 0.25 \text{ seconds.}$$

At $t_f = 0.25$ seconds:

$$v(t_f) = 0.020833a_2.$$

Remembering that the position ($s(t)$) is:

$$s(t) = \int v(t) dt = \frac{a_3t^4}{4} + \frac{a_2t^3}{3} + \frac{a_1t^2}{2} + a_0t + C = \frac{-2.66667a_2t^4}{4} + \frac{a_2t^3}{3} + C.$$

where at $t = 0$, $s(0) = 0$ such that $C = 0$. By substitution for $t_f = 0.25$ seconds,

$$s(t_f) = s(0.25) = 0.00260413a_2.$$

Next, the slow velocity of the slider must be found in order to complete the motion profile equations. This is found in the following equation:

$$47'' = 2(s(\text{in acceleration zones})) + s(\text{during constant velocity})$$

$$\text{where } s(\text{during constant velocity}) = \text{slew velocity} * 3.5 \text{ seconds.}$$

Therefore:

$$\text{slew velocity} = \frac{47'' - 2(s(\text{in acceleration zones}))}{3.5 \text{ seconds}}$$

$$\text{where slew velocity} = v(t_f) = 0.020833a_2.$$

Therefore:

$$0.020833a_2 = \frac{47'' - 2(s(\text{in acceleration zones}))}{3.5 \text{ seconds}}$$

Now recall that:

$$s(\text{in acceleration zones}) = 0.00260413a_2.$$

By substitution:

$$0.020833a_2 = \frac{47'' - 2(0.00260413a_2)}{3.5 \text{ seconds}}.$$

Which yeilds:

$$a_2 = 601.6 \text{ and } a_3 = -1604.269.$$

This formulation leads to the following equations as shown in Chapter 5:

$$v(t) = -1604.3t^3 + 601.6t^2 \quad (\text{in/sec}) \quad 0 < t < 0.25 \text{ seconds} \quad [\text{E7}],$$

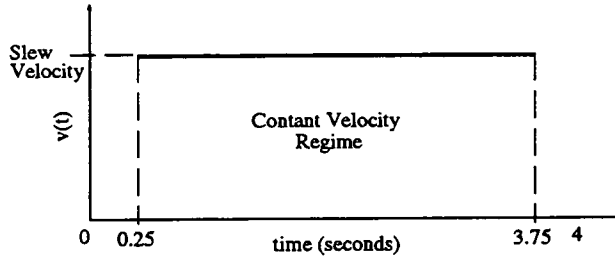
$$a(t) = -4812.8t^2 + 1203.2t \quad (\text{in/sec}^2) \quad 0 < t < 0.25 \text{ seconds} \quad [\text{E8}],$$

$$s(t) = -401.067t^4 + 200.433t^3 \quad (\text{in}) \quad 0 < t < 0.25 \text{ seconds} \quad [\text{E9}],$$

$$\text{and } j(t) = -9625.6t + 1203.2 \quad (\text{in/sec}^3) \quad 0 < t < 0.25 \text{ seconds} \quad [\text{E10}].$$

These equations show that the required slew velocity to meet the specified requirements is approximately 12.53 in/sec. Also, the position of the slider at the end of the acceleration zone is at 1.565 inches from the beginning position.

Next, the constant velocity region of the motion profile is analyzed:



The next set of initial condition for the constant velocity regime are $t_0 = 0.25$ seconds, $t_f = 3.75$ seconds, $v(t_0) = \text{slew velocity} = 12.53$ in/sec, $v(t_f) = \text{slew velocity} = 12.53$ in/sec, $a(t_0) = 0$ and $a(t_f) = 0$.

These conditions lead to the following equations:

$$v(t) = 12.53 \quad (\text{in/sec}) \quad 0.25 < t < 3.75 \text{ seconds} \quad [\text{E11}],$$

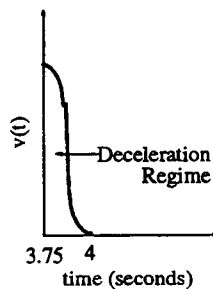
$$a(t) = 0 \quad (\text{in/sec}^2) \quad 0.25 < t < 3.75 \text{ seconds} \quad [\text{E12}],$$

$$s(t) = 12.53(t - t_0) + 1.565 \quad (\text{in}) \quad 0.25 < t < 3.75 \text{ seconds} \quad [\text{E13}],$$

$$\text{and } j(t) = 0 \quad (\text{in/sec}^3) \quad 0.25 < t < 3.75 \text{ seconds} \quad [\text{E14}].$$

Now, after the constant velocity region of the motion profile, the slider has moved approximately 45.42 inches from the beginning position.

Finally, the deceleration zone of the profile is analyzed:



For the deceleration region of the profile, the initial condition of the system are $t_0 = 3.75$ seconds, $t_f = 4$ seconds, $v(t_0) = \text{slew velocity} = 12.53$ in/sec, $v(t_f) = 0$, $a(t_0) = 0$ and $a(t_f) = 0$, $s(t_0) = 45.42$ " and $s(t_f) = 47$ ". From these initial conditions, the following four equations can be formed:

$$v(t_0) = v(3.75) = 12.53 = b_3(3.75)^3 + b_2(3.75)^2 + b_1(3.75) + a_0,$$

$$v(t_f) = v(4) = 0 = b_3(4)^3 + b_2(4)^2 + b_1(4) + b_0,$$

$$a(t_0) = a(3.75) = 0 = 3b_3(3.75)^2 + 2b_2(3.75) + b_1,$$

$$a(t_f) = a(4) = 0 = 3b_3(4)^2 + 2b_2(4) + b_1.$$

These four equations can yield a total of four unknowns which enables us to find the solution for all the constants. Putting these equations in the matrix form of $A \cdot b = C$:

$$\begin{bmatrix} 3.75^3 & 3.75^2 & 3.75 & 1 \\ 4^3 & 4^2 & 4 & 1 \\ 3*3.75^2 & 2*3.75 & 1 & 0 \\ 3*4^2 & 2*4 & 1 & 0 \end{bmatrix} * \begin{bmatrix} b_3 \\ b_2 \\ b_1 \\ b_0 \end{bmatrix} = \begin{bmatrix} 12.53 \\ 0 \\ 0 \\ 0 \end{bmatrix}.$$

The unknown constant vector can be solved as $b = A^{-1} * C$ as yields the following:

$$\begin{bmatrix} b_3 \\ b_2 \\ b_1 \\ b_0 \end{bmatrix} = \begin{bmatrix} 1603.84 \\ -18644.64 \\ 72172.8 \\ -93022.72 \end{bmatrix}.$$

These constants can be substituted back into the generic profile equations to obtain:

$$v(t) = -1603.84t^3 - 18644.64t^2 + 72172.8t - 93022.72 \quad (\text{in/sec})$$

for $3.75 < t < 4$ seconds [E15],

$$a(t) = 4811.52t^2 - 37289.28t + 72172.8 \quad (\text{in/sec}^2)$$

for $3.75 < t < 4$ seconds [E16],

$$s(t) = 400.96(t^4 - t_0^4) - 6214.88(t^3 - t_0^3) + 36086.4(t^2 - t_0^2) - 93022.72(t - t_0) + 45.42$$

(in) for $3.75 < t < 4$ seconds [E17],

$$\text{and } j(t) = 9623.04t - 37289.28 \quad (\text{in/sec}^3) \quad \text{for } 3.75 < t < 4 \text{ seconds [E18].}$$

These formulations show the development of the motion profiles which are used in the analysis and design of the inspection station positioning device.

Appendix C. C Program to find Carriage Bar Dimensions for Minimum Deflection

```
/**
 * Programmer: Jeffrey W. Buck
 * Date: 2/22/96
 * Program title: Deflection.c
 *
 * Purpose: This is a program to find the dimensions of the
 *          carry bar that will minimize the deflection of the
 *          beam under loading conditions for a one drive
 *          system.
 */

#include<stdio.h>
#include<math.h>
#include<stdlib.h>

main ()
{
    int i;
    float y,y_max,volume,height,height_max,width,length,Weight,I,E,h;

    /**
     * Declaration of Variables
     */

    length=90; /* where 90 is in the units of inches*/
    h=1000; /* the number of iteration points */
    E=10E6; /* the modulus of elasticity for aluminum in psi */
    volume=225; /* the total volume of the bar in inches cubed */
    Weight=46.5; /* the weight of the bar */
    height_max=12; /* the maximum allowable height */

    printf("The dimensions of the bar to minimize the deflection of the bar are as
follows:\n");

    /**
     * Starting points
     */

    width = 0.125;
    y=15;

    /**
     * Beginning of the main routine
     */

    for (i=1; i<=h; ++i)
    {
        height=11.811;
```

```

I=width*pow(height,3)/12;    /* for a rectangular bar */
y_max = Weight*pow(length,3)/(24*E*I);
if (y>=y_max)

    /**
    * The output is printed out for display
    **/

    printf("y_max = %f  length = %f  width = %f  height=
%f\n",y_max,length,width,height);
    y=y_max;

}
}

```

Appendix D. C Program which Calculates the Loads and Deflections of the System

```
/******
*
*   Programmer: Jeffrey W. Buck
*   Date: February 23, 1996
*   Title: analysis.c
*
*   Purpose: To analyze the loading, stress, deflection
*            force and moments present in the system for
*            the given input. Deterministic inputs are the
*            number of drive systems (1 or 2), the load in weight,
*            the material and the carry bar dimensions.
*
******/

#include<stdio.h>
#include<math.h>
#include<stdlib.h>

main()
{
    int number_drives;
    float
weight,E,length,height,width,acceleration,Max_stress,Max_moment,Max_deflection,Max
_force;
    float I,c,Z;

    /***
    * here the material under consideration is aluminum
    ***/
    E=10E6;

    printf("Input the number of drive systems under analysis:");
    scanf("%d",&number_drives);
    printf("\nInput the total distributed weight the bar will carry in pounds:");
    scanf("%f",&weight);
    printf("\nInput the length of the carry bar between the two ends in inches:");
    scanf("%f",&length);
    printf("\nInput the height of the bar from top to bottom in inches:");
    scanf("%f",&height);
    printf("\nInput the width (thinckness) of the bar from front ot back in inches:");
    scanf("%f",&width);
    printf("\nInput the acceleration term present in the system in inches/sec^2:");
    scanf("%f",&acceleration);

    I=width*pow(height,3)/12;    /* for a rectangular bar */
    c=height/2;
    Z=I/c;
```

```

        if(number_drives==1)                /* this means the system is fixed at
one end                                     and free but guided
at the other end */
    {
        Max_force=weight/386*(386+acceleration);
        Max_moment=weight/386*(386+acceleration)*length/3;
        Max_deflection=weight/386*(386+acceleration)*pow(length,3)/(24*E*I);
        Max_stress=Max_moment/Z;
    }
    if(number_drives==2)                    /* this means that both ends are fixed
and guided */
    {
        Max_force=weight/386*(386+acceleration)/2;
        Max_moment=weight/386*(386+acceleration)*length/12;
        Max_deflection=weight/386*(386+acceleration)*pow(length,3)/(384*E*I);
        Max_stress=Max_moment/Z;
    }

    /**
    * The output is printed to the display
    ***/

    printf("\nFor these conditons: Max_force = %f lb., Max_moment = %f in-
lb.,",Max_force,Max_moment);
    printf("\nMax_deflection = %f inches & Max_stress = %f
psi.",Max_deflection,Max_stress);

    /* end of program */
}

```

Appendix E. MATLAB Program for Control System Analysis

```
%%%%%%%%%%
%   Programmer:  Jeffrey W. Buck
%   Program Description:  Control System Analysis
%   Program Title:      Control.m
%   Date of Completion:  June 20,1996
%%%%%%%%%%

clg
clear
hold off

% Define Variables and their values

J=0.004266;
B=0;
L=0.0057;
R=0.45;
Kt=5.21875;
Ke=0.1967;

%%%%%%%%%
% Note:  for this analysis, the effects of the load and friction
%        torque have been neglected to simplify the analysis. This
%        implies that the results obtained are only approximate
%        solutions.
%%%%%%%%%

% Gain Values to be determined
%   By evaluating the performance of the system on the control
%   techniques used in this program, the following gain values
%   can be set to achieve the desired system characteristics as
%   chosen by the control designer.

K1=0.006
K2=0.00001

% Determination of values used in transfer function polynomial
%
%   the form of the polynomial is:
%
%    $G = (a_3 s^3 + a_2 s^2 + a_1 s + a_0) / (b_3 s^3 + b_2 s^2 + b_1 s + b_0)$ 
%   where the numerator and denominator values represent the
%   constant values corresponding to the respective order of
%   the Laplace differential operator

a0=K1*Kt*2048/2/pi;
a1=0;
a2=0;
a3=0;
```

```

b0=K1*Kt*2048/2/pi;
b1=(R*B+Kt*K2*2048/2/pi+Ke*Kt);
b2=(J*R+L*B);
b3=L*J;

```

```

num=[a3 a2 a1 a0];
den=[b3 b2 b1 b0];

```

```

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%
%      The Root Locus Section
%

```

```

axis('square')
rlocus(num,den);
grid
hold on
title('180 Locus')

```

```

hold off

```

```

%
%      End of Root Locus Section
%

```

```

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
pause

```

```

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%
%      The Frequency Response Section
%

```

```

%      1. Bode Plot

```

```

axis('normal')
bode(num,den);
title('Bode Plot')
[M,phase]=bode(num,den);

```

```

%      the logspace function equally distributed the values on the
%      the logarithmic scale

```

```

pause

```

```

%      2. Polar Plot for the Open-Loop System

```

```

clg
axis([-1,1,-1,1]); % axis([lower x, upper x, lower y, upper y])
polar(phase*pi/180,M)
grid

```


Appendix F. SIMULINK and MATLAB Programs for Control System Simulation

The MATLAB programs used to generate the position and velocity motion profiles are given below. The SIMULINK simulation model for the position input is given next and then the simulation model for the velocity input is given last.

The MATLAB program to generate the position data points for simulation:

```
%%%%%%%%%%
% Programmer: Jeffrey W. Buck
% Program Description: Generates data of Position versus Time
%                    to match velocity profile
% Program Title: position_data.m
% Date of Completion: July 15,1996
%%%%%%%%%%

for t = 0:0.01:0.25,
    j= t*100+1;
    T(j,1)= t;
    S(j,1)= -401.067 * t^4 + 200.433 * t^3;
end

for t = 0.26:0.01:3.75,
    j= t*100+1;
    T(j,1)= t;
    S(j,1)= 12.53*(t-0.25)+1.565;
end

for t = 3.76:0.01:4.0,
    j= t*100+1;
    T(j,1)= t;
    S(j,1)= 1603.84/4*(t^4-3.75^4) - 18644.64/3*(t^3-3.75^3) +
            72172.8/2*(t^2-3.75^2) - 93022.72*(t-3.75) + 45.42;
end

for t = 4.01:0.01:5.0,
    j= t*100+1;
    T(j,1)= t;
    S(j,1)= 1603.84/4*(4^4-3.75^4) - 18644.64/3*(4^3-3.75^3) +
            72172.8/2*(4^2-3.75^2) - 93022.72*(4-3.75) + 45.42;
end

% End of Program
```


The MATLAB program to generate the velocity data points for simulation:

```
%%%%%%%%%%
%   Programmer:  Jeffrey W. Buck
%   Program Description: Generates data of Velocity versus Time
%                       to match velocity profile
%   Program Title:    velocity_data.m
%   Date of Completion:  July 15,1996
%%%%%%%%%%

    for t = 0:0.01:0.25,
        j= t*100+1;
        T(j,1)= t;
        V(j,1)= -1604.3 * t^3 + 601.6 * t^2;
    end

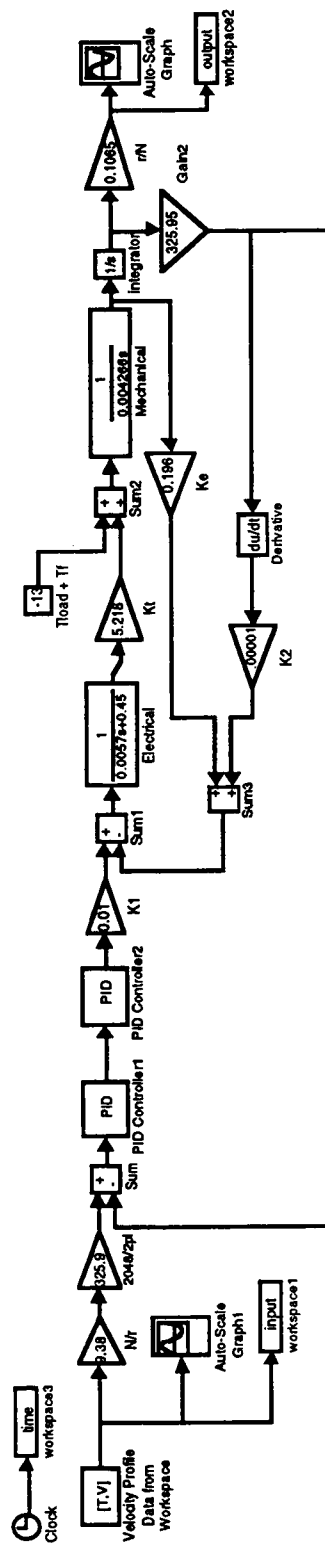
    for t = 0.26:0.01:3.75,
        j= t*100+1;
        T(j,1)= t;
        V(j,1)= 12.53;
    end

    for t = 3.76:0.01:4.0,
        j= t*100+1;
        T(j,1)= t;
        V(j,1)= 1603.84 * t^3 - 18644.64 * t^2 + 72172.8 * t - 93022.72;
    end

    for t = 4.01:0.01:5.0,
        j= t*100+1;
        T(j,1)= t;
        V(j,1)= 0;
    end

%   End of Program
```

The SIMULINK model to simulation the control system for a velocity input:



Vita

Jeffrey Wayne Buck was born in the rocky mountain high of Fort Collins, Col. at the stroke of 1:01 a.m. on the morning of October 1, 1971. With such a wonderful place as the United States of America to grown up in, Jeff's parents (Wayne and Vicki) decided that he should move around a lot so that he could get to see many things and many people. In his early years, Jeff lived in Colorado, Iowa and Minnesota before the grand state of Tennessee lured him to stay. When Jeff was four years old, he received a baby sister by the name of Crystal. Jeff and Crystal (known as Moe by those close to her) were inseparable. Of course that included many occurrences of hair pulling and rock throwing along the way. With Wayne, Vicki and Crystal, Jeff grew up to love his family, the smell of the fresh outdoors, fishing, camping, football, basketball, baseball, country music and downright friendly people. Most of Jeff's life was spent growing up in a small town just west of Nashville, Tn., known as Kingston Springs.

Eventually, Jeff graduated from Harpeth High School in June of 1990. At Harpeth (where democracy was often taught but rarely practiced) Jeff managed to obtain the rank of Salutatorian while also participating in the football and basketball as well as other social activities. Upon graduation, Jeff elevated himself to the school of higher learning at the University of Tennessee. At the University of Tennessee, Jeff enlisted into the College of Engineering and dashed any hope of a truly social college experience. While majoring in mechanical engineering, Jeff grew into manhood with the help of family, friends and his beloved fraternity (Kappa Alpha Order). After completing his undergraduate career in May of 1994, Jeff decided that he would continue his education pursuing a Master of Science in Mechanical Engineering. While in graduate school, Jeff met his wife to be (Lori Ann) as she was preparing to complete her undergraduate degree in Public Relations from the College of Communications. On June 8, 1996, Jeff and Lori were married after dating for

over two years as Jeff worked to complete his Master's degree. In August of 1996, Jeff received his Masters of Science degree from the University of Tennessee and ventured into the real world in search of ways to apply all the knowledge accumulated in over 19 years of education.