INTEGRATED INSPECTION SYSTEM IN MANUFACTURING: VISION SYSTEMS

by

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(ABSTRACT)

The purpose of this report is to demonstrate the effective use of the Systems Engineering Process in prototype system development, as well as the impact of integrated inspection systems utilizing vision systems in a manufacturing environment.

The report demonstrates the benefits of applying the systems engineering process as a structure organizational approach toward prototype development. The foundation of the report lies within the systems theory to identify and solve design concerns.

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Thanks are due to all of my colleagues for their support and encouragement.

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TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

CHAPTER I

INTRODUCTION

1.1 History

The Integrated Inspection Systems project was developed by Philip Morris, U.S.A., to improve quality to the customer, provide instantaneous view of the process, and early detection and prediction of process problems. In the early 1970's, cigarette manufacturing machinery could make 4,000 individual cigarettes per minute. The cigarettes were loaded into trays, transferred to the packer, which packaged twenty cigarettes into a pack at a production speed of 200 packs per minute.

Typically, the output of two packers was fed along two parallel conveyors. A person visually inspected both product streams at an astounding 400 packs per minute. This rate was achieved only by manually stopping one of the rows and comparing them as a group. Mirrors were utilized to provided a view of the opposite side of the packs. This method of inspection was only partially effective.

In the early 1980's, the next generation of making and packing machinery evolved. These highly-automated machines produced more than 8,000 cigarettes per minute and packed 400 plus per minute. This increase in production speed severely reduced the operator's ability to visually inspect the finished product.

One making and packing operator is located at each complex. Each operator is responsible for the product produced on their assigned machine as well as for setting up the manufacturing materials, such as cigarette paper, wrapping materials, tax stamps, cartons, and cases to produce the correct product to specification.

The new layout of these complexes made it even more difficult and ineffective for the operator to inspect the finished packs. The newer generation machinery was larger and more complex, they required more attention to the machine than to the manufacturing process. Assembled packs on the conveyor immediately disappeared behind the packer. Since manufacturing speeds were doubled, inspectors could no longer perform on-line inspection techniques. Instead, quality personnel sampled one pack per hour from each of the 50 complexes.

Although the new generation of machines operate far better, all machines occasionally make assembly errors. They need adjustment, cleaning, and maintenance. The defects occur randomly and in bursts. At over 400 packs per minute, statistically sampling by quality inspectors is impossible. Throughout the early and mid 1980's, engineers investigated various approaches for inspecting cigarettes on-line. Discrete detectors were difficult to setup and verify and could not make sophisticated measurements. They also decreased maintainability which decreased machine performance. Speed, cost, performance, and inspection system complexity were all barriers to using machine vision systems.

Application of machine vision systems would have been difficult in the mid 1980's. Technology was still immature and unable to meet basic performance requirements. The newer generation machines were using 1970's technology. It combined various photocells and inductive sensors to provide only a course check on the assembly process preventing downstream jams. However, it did not provide reject cause data. The existing inspection systems were an inspection/rejection tool, not a process control tool.

Developments in machine vision industry provided improved choices for inspection. Improved hardware has drastically increased operating speeds while costs were reduced. System maintainability, manability, and supportability had dramatically increased. The time to develop a prototype cigarette inspection system had come.

1.2 Objective

The objective of this project is to develop an integrated cigarette inspection system using machine vision. The conceptual design and in-house prototype development would be accomplished utilizing the Systems Engineering Process [2].

Applying the systems approach to the project will provide the necessary information to determine whether or not the prototype system is feasible for a manufacturing environment and the overall impact of the technology.

Specifically, the objective is to evaluate machine vision technology in cigarette manufacturing. The systems engineering process is used as a process management structure to provide the design team with the necessary data to continue or abandon the prototype development. The information obtained from the systems design process will also be used in the formulation of the project closure recommendation. If the system evaluation supports factory implementation then the data from the prototype model will be used to support a factory implementation plan.

1.3 Definition of Need

Justification for the system is established by decreasing the total cigarette surface defects by 71% and quality costs by reducing the false defect rejection rate by 20%. Surface rejects attribute to a large portion of percent of defective packs being rejected. Utilizing the system would demonstrate a decrease in percent defective packs by 75%.

Machine vision for cigarette inspection is a means to achieving the goal of becoming the lowest cost producer of the highest quality products. International competition has increased quality awareness in the tobacco industry. Entire shipments are returned to the manufacturer when random sampling or total product inspections are labeled defective.

Cigarette manufacturing is attempting to establish a Total Quality Initiative (TQI) program. One of the objectives in the TQI program is to "quality empower the operator". The objective of "quality empowering the operator" is to increase the operator's responsibility and accountability for inspecting product quality. Management previously relied on a quality inspector to perform the task. The machine operator did not posses the tools necessary for determining the quality of the product. The operator could not determine the condition of their process. The only measure the operator had was throughput, or actual production.

The operator would determine the wellness of their process by monitoring the rejects. They would reach into the rejection bins to verify that only defective cigarettes were being rejected. The operator needed an information system that could provide him/her with process information.

The vision system was capable of inspecting, rejecting, categorizing, storing, and displaying the defects real-time to the operator. From this information the operator would be provided with process tending charts.

In summary, the overall justification for the development of the system would be to improve the product quality by 71%, reduce quality cost by 20% through automated inspections and data collection, and improve efficiency of cigarette manufacturing machines by 5%.

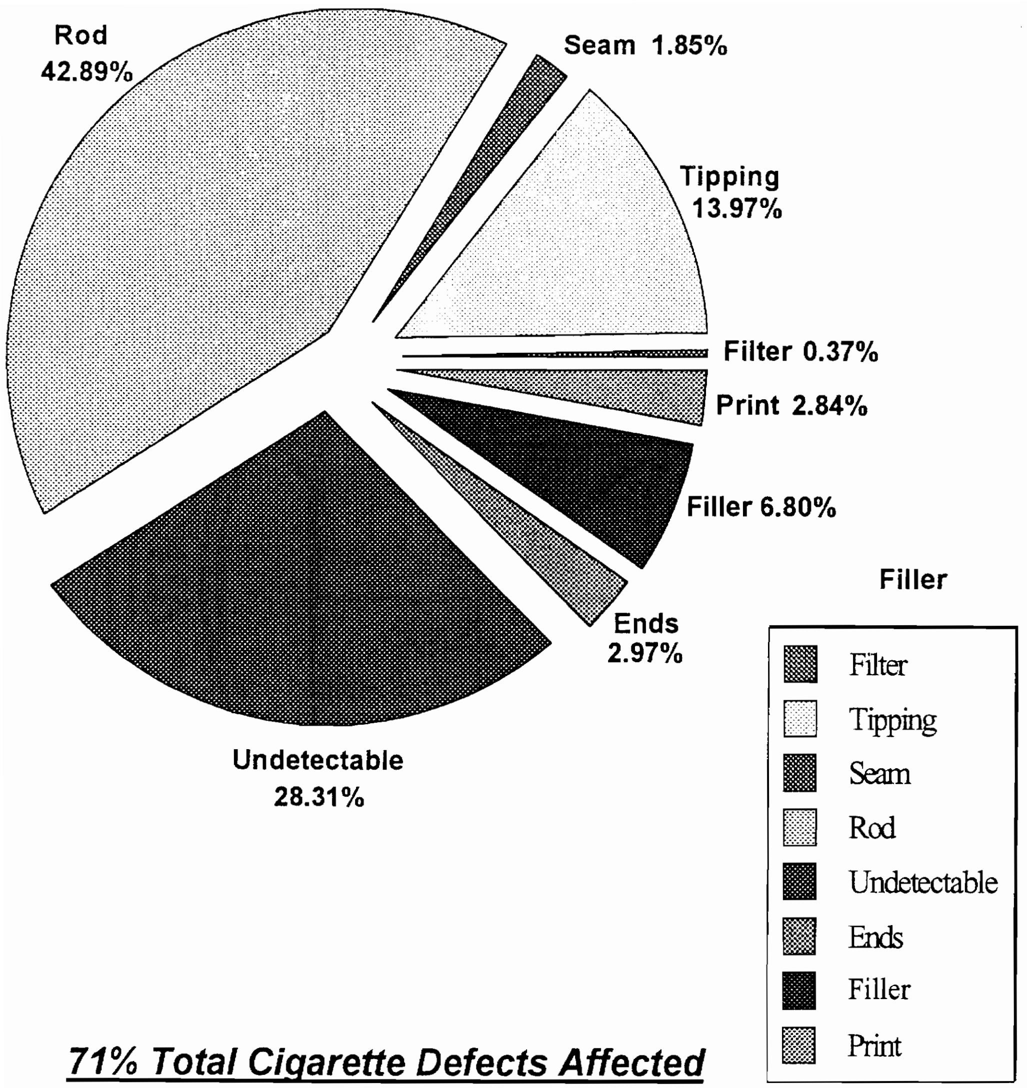


Figure 1.1: System Quantitative Goals

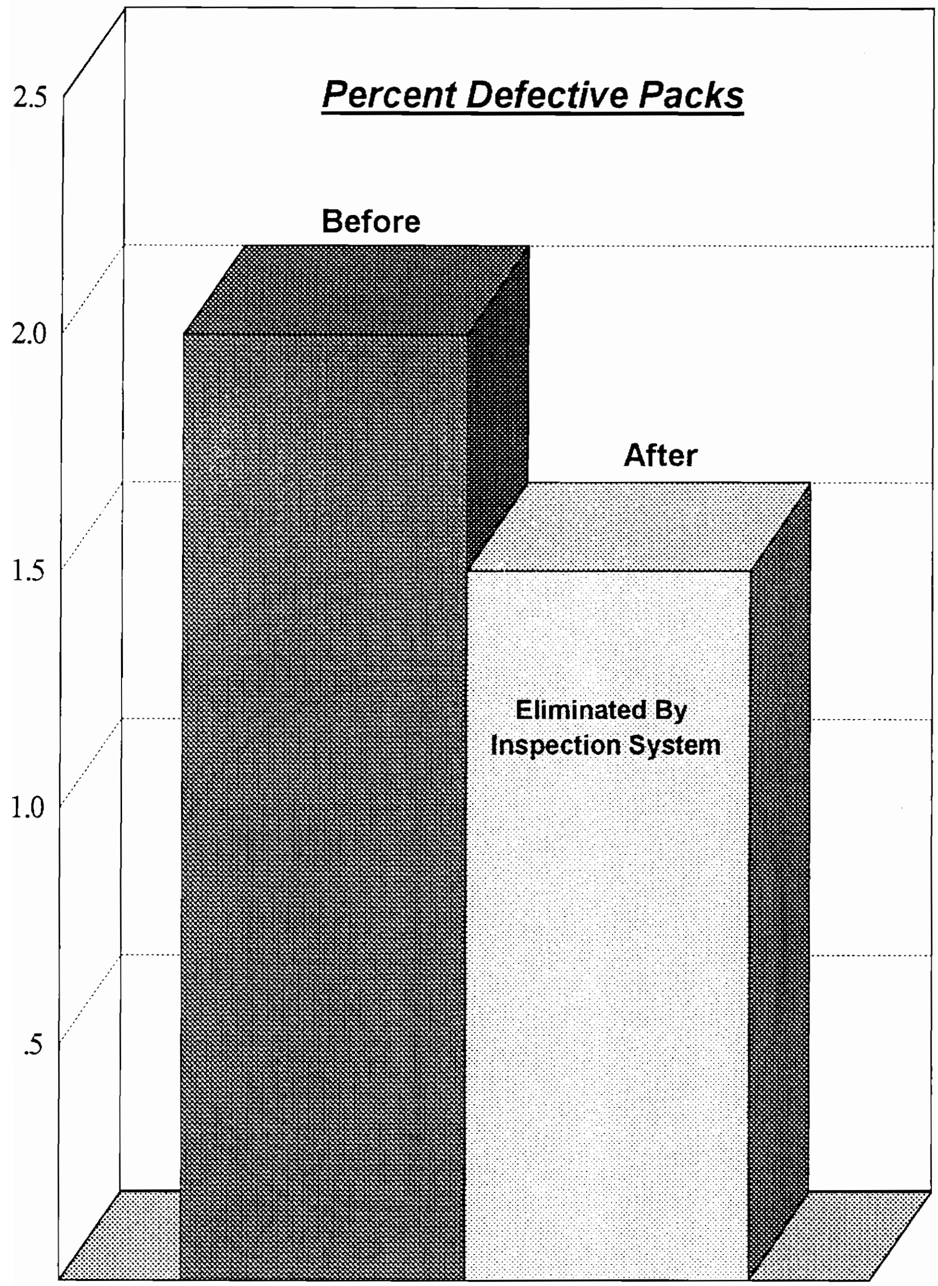


Figure: 1.2: Projected Percent Defective Packs Eliminated By Inspection System

CHAPTER II

SYSTEM DESIGN PROCESS

2.1 Conceptual System Design and Organization

The systems design process begins with an identified need and feasibility study for the purpose of establishing design parameters [2]. The design parameters will be used to determine engineering resource allocation, organizational and system requirements, constraints, and design criteria.

A need was established by production management and the quality assurance department for an integrated inspection system that is capable of inspecting cigarettes at manufacturing speeds. The system should inspect each cigarette for external rod and filter defects. The system should also be able to record, store, and display appropriate information to the operator.

Three alternative methods existed to perform the task: machine vision, pressure drop drum system, and infrared optical system. Machine vision is a new technology that would have to be dealt with on the manufacturing floor. This would impact the maintenance, reliability, maintainability and supportability. The training cost alone would be very costly and resource intensive. The pressure drop drum systems have not been very effective in previous evaluations. They are unreliable with regard to surface defects and required extensive and frequent calibration. The maintenance would be extensive and the reliability is poor due to the pneumatics. Although the training cost would be very minimal, the effectiveness of the system is unacceptable. The infrared (IR) optical system employed a nuclear source which also measured the tobacco density. The density measurement system was already installed on the machinery. The IR optical system could be added on the present control system. The IR optical system with the nuclear source was very old technology and possessed a safety concern.

Economically, machine vision is the most costly in both initial development and resource allocation. The other systems are not as costly, but do not provide the effectiveness or performance capabilities of machine vision.

Table 2-1 is a summary of the cigarette inspection systems verses defect categories that occur in the cigarette manufacturing process. The defect categories were chosen by quality assurance due to their frequency of occurrence and probability of reducing the defective product reaching the customer.

Table 2.1

Evaluation of Cigarette Inspection Systems vs. Cigarette defect Category

Defect Category	Machine Vision	Pressure Drop System	IR Optical
Cig. Ends Loose/Void	Yes	Yes	Yes (Void)
Torn or Ragged Cut	Yes	No	No
Mashed End	Yes	No	No
Cig. Rod Torn	Yes	Maybe	No
Stem Hole	Yes	Maybe	Maybe
Incomplete Filled Rod	No	Maybe	Yes
Broken Cig.	Yes	Yes	No
Paper Break	Yes	No	No
Rod Hole Indentation	Yes	No	No
Smeared Dirty Rod	Yes	No	Maybe
Water Spot	Maybe	No	Yes
Discoloration	Yes	No	No
Tobacco Spots	Yes	No	Maybe
Cig. Stuck Together	Yes	No	No
Cig. Die No. Exposed	Yes	No	Maybe
Print Position	Yes	No	No

Table 2.1.1

Evaluation of Cigarette Inspection Systems vs. Cigarette defect Category

Defect Category	Machine Vision	Pressure Drop System	IR Optical
Open Seam	Yes	Maybe	Maybe
Short in Seam	Yes	No	Yes
Tear Slit Ragged Seam	Yes	No	No
Creased Seam	Yes	No	No
Filter Fall Off	Yes	Maybe	No
Air Leak	Maybe	Yes	No
Tipping Adhesive	No	Maybe	No
Missing Component	Yes	Yes	No
Smeared Dirty Tipping	Yes	No	No
Extra Tipping Paper	Yes	No	No
Tear Slit Hole Tipping	Yes	No	No
Skewed Tipping	Yes	No	No
Long or Short Tipping	Yes	No	No
Smeared Dirty Filter	Yes	No	No
Charcoal Scatter	Yes	No	No
Spots	Yes	No	Maybe

A project development team was formed to represent all affected organizations, top-down management support, manufacturing, quality assurance, adequate vision technology and a good user/vendor working relationship. The project development team charter was to serve as a steering committee to ensure that the development of such a prototype system could emerge as a commercial product and not an ongoing research and development project. Historically, many projects of this magnitude and nature had a problem reaching closure. This was one of the foremost objectives in using the system engineering process.

The project development team was in agreement that the machine vision inspection system had the most to offer manufacturing. It was also agreed that a cultural impact was inevitable. Learned behaviors would have to be changed or modified. We were essentially beginning a project that may be used as the primary tool that could dictate the way we do business in the future.

The system operational requirements are defined from its operation concept. One prototype vision inspection system would be developed. The system would be developed by the Applied Technology Group in engineering. The prototype system would be tested and installed on a cigarette machine complex at the Stockton Street Manufacturing Facility.

The system was utilized to determine the effectiveness of the machine vision inspection system in cigarette manufacturing environment. The systems objectives are to inspect each cigarette at manufacturing speeds. The cigarette inspection goals include 360 degree inspection, an inspection rate of 10,000 cigarettes per minute, adaptability to existing machinery, to provide the operator with an advanced human-machine interface, and provide data collection.

The operating characteristics of the system could not hinder the operator from their normal tasks. The system also could obstruct areas of the machine that require frequent maintenance. There were several critical performance parameters that the system needed to meet to be successful. The first, the system had to interact with the machine operator. The second, due to the new technology of vision system the system had to be supportable from a causal user perspective. The user interface had to be intuitive and not complex. This guided the design to a multi-user platform. The technical complexity of the system needed to be maximized to increase its performance, but the presentation of the system complexity had to be minimized.

The system development was scheduled for one year and the factory evaluation was scheduled for an additional year. During the factory testing the system would be supported by the engineering design team. They would provide the technical support and maintenance for manufacturing. Engineering would also be responsible for obtaining data to determine utilization requirements, effectiveness factors, and the impact on the manufacturing environment.

A preliminary maintenance plan was established to form the operational requirements. The plan would not only support the prototype system, but would provide the development team with valuable feedback to determine the impact of the existing maintenance organization. At the organizational level the prototype system would require cleaning (dust removal from camera lens), and visual inspection. The intermediate level would be responsible for removal and replacement of modules or assemblies. A qualified individual would be responsible for calibration, software security, and system troubleshooting[4]. During the prototype evaluation, engineering will serve this function. Until the evaluation and testing of the system is completed in the factory it is difficult to determine the overall impact the system will have on manufacturing. At the depot level of maintenance will be the component or system manufacturers. The prototype system will be supported by two spare units. One will be installed at the development site and one will be used as a hot stand-by spare at the factory.

The system specification is derived from the preliminary systems analysis, including operational and maintenance requirements [2]. The system specifications for the prototype are described below:

(1) System Description-High speed inspection system using machine vision for the inspection. System is required to inspect each cigarette at manufacturing speeds and provide a human-machine interface. System must also provide data collection and data storage.

(2) Operational Requirements-System must be capable of inspection speeds of 10,000 ppm and provide single defect rejection capability. System must inspect for external and filter defects. 360 degree inspection coverage is required.

(3) System Maintenance-Primary support will be

provided by engineering. Minimal support will be provided by manufacturing to minimize the impact of evaluating the system on existing production equipment.

(4) Performance and Physical Characteristics-System must be capable of high speed image processing and scan rates. System must have a graphical user interface for setup, maintainability, and supportability. System implementation cannot obstruct readily accessible areas of the machine. A video monitor must be configured and installed to ergonomic specifications.

(5) Effectiveness Measures-System goal is to achieve 70% efficiency on the defined defects. System should have a negligible impact on current operators tasks. The cost of the units must not exceed $50,000 each. Spare parts availability shall be 100%. Mean time between intermediate maintenance shall be greater than 1000 hrs. Mean time between organizational maintenance shall be 7.5 hrs.

(6) Design Specifications-System enclosure shall have NEMA 12 rating. All cables male/female type for

interchangeability. All adjustments fixed or precision if possible. Video monitor shall have NEMA 12 rating. The front of the monitor must have a protective cover to protect against implosion. Vision system input device must be suitable for production environments and manufacturing users.

(7) Construction-All design shall meet or exceed NEC and Philip Morris Engineering Specifications [4].

(8) System Documentation-Drawings, operational manual, spare parts list, and vendor documentation shall be completed prior to installation.

(9) Quality Assurance Test Plan-Vision process inspection system test and evaluation plan shall be completed prior to installation.

A functional block diagram of the prototype system is illustrated in figure 2.1.

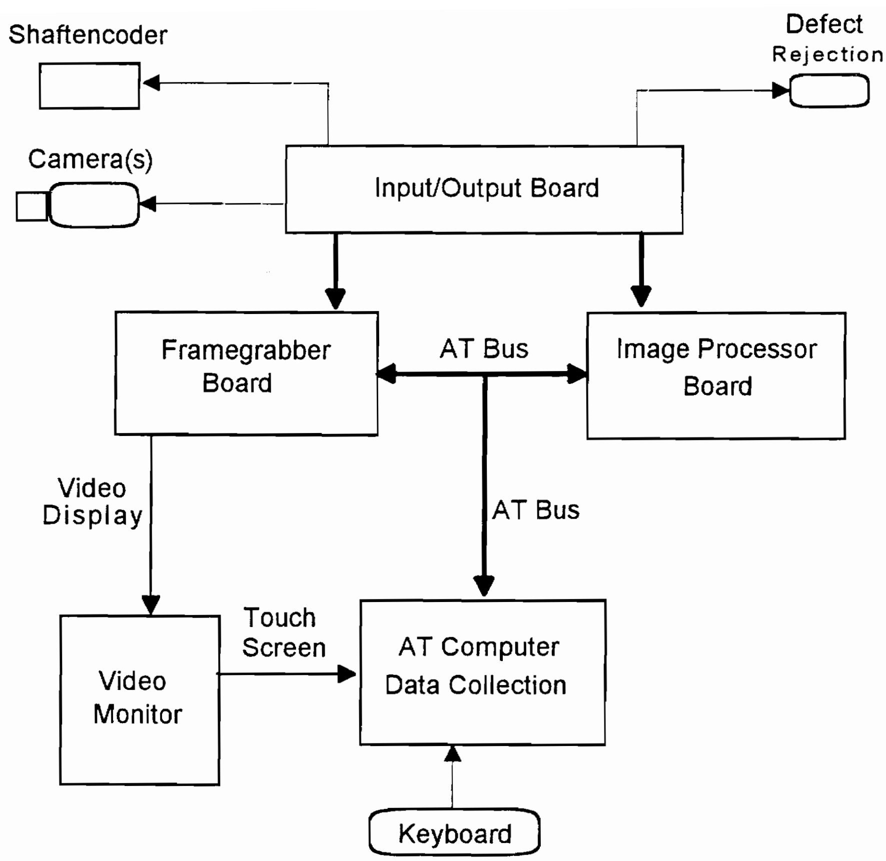


Figure 2.1: Vision Inspection System Architecture

CHAPTER III

PRELIMINARY SYSTEM DESIGN

3.1 System Function Analysis

The initial step prior to constructing the system functional analysis is the formulation of a functional description of the system and components of the system development and operation [2].

The cigarette vision inspection system is comprised of a vision process controller, two optical camera boxes, three cameras, strobe light, fiber-optic light guides, shaft encoder, and the mechanical rejection assembly.

The first camera inspects greater than 180 degrees of the cigarette as it is transferred via a series of fluted drums. The cigarettes are held in the flutes by vacuum. The cigarettes are transfer from drum to drum by releasing the vacuum on the transferring drum and maintaining the vacuum on the subsequent drum. During the cigarette transfer through the machine the other side of the cigarette is positioned for the second camera. The second camera also inspects greater than 180 degrees of the cigarette to guarantee 360 degree inspection of each cigarette. When a defective cigarette is identified the rejection valve will prevent the transfer process. The defective cigarette is held on to the final inspection drum and mechanically removed via a stripping action by the rejection pan. The rejection pan is equipped with an air blow-off to move the defective cigarettes forward and down into the existing machines rejection bins.

The operator interface is provided by the touch screen video monitor. The monitor is a SVGA color with an integral touch screen. The touch screen allows the operator to activate various controls by using a visual representation of the process as they interact with the system. An image processing technique called framesplitting enables the vision processor to obtain portions of the images from the cameras an treat them as one. This will allow the system to simultaneously inspect multiple views of the cigarettes and provides the operator with each view of the cigarette being inspected.

Figure 3.1 is an illustration of the vision inspection system process. Figure 3.2 is a functional flow diagram of the vision inspection system.

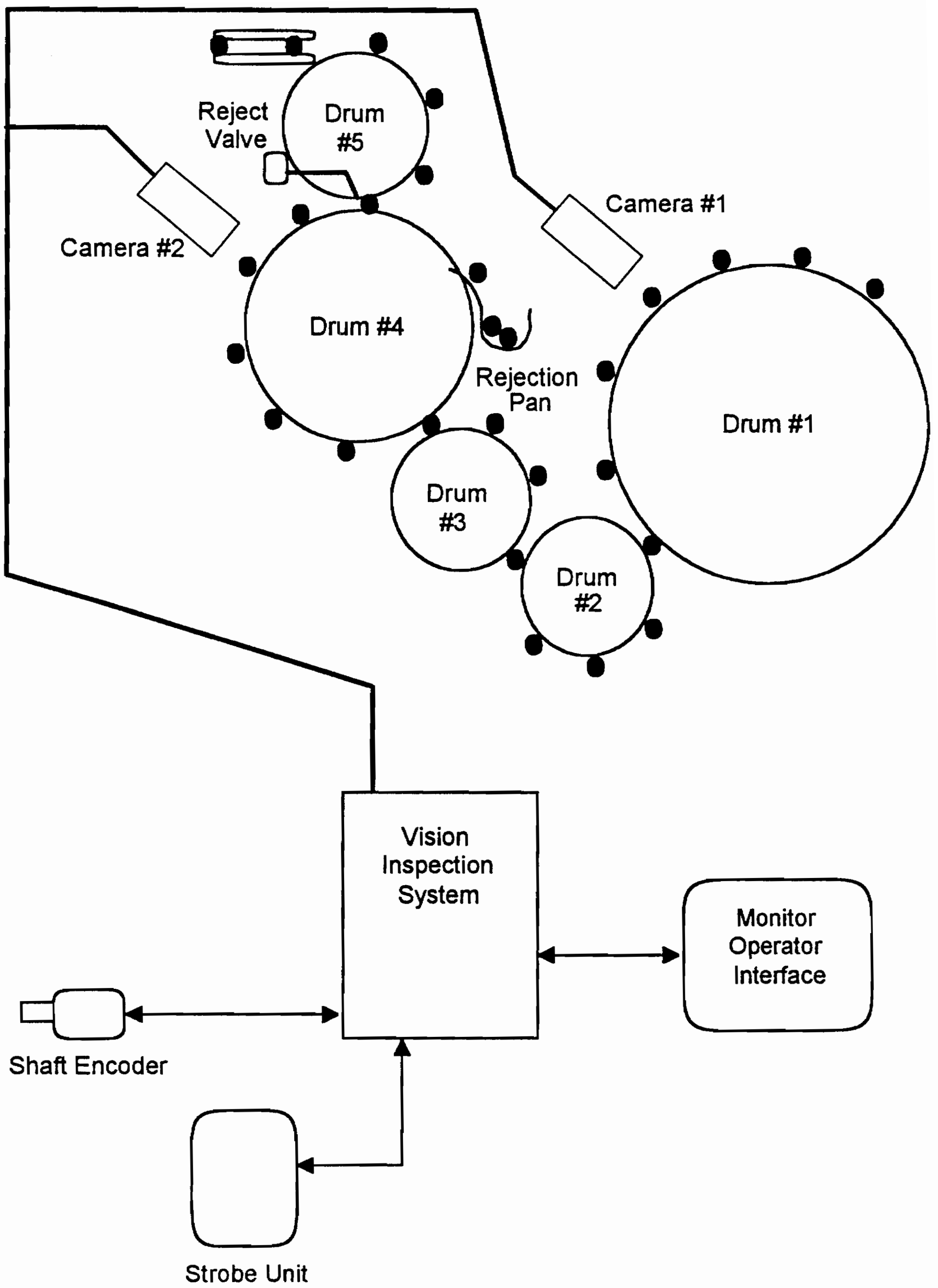


Figure 3.1: Vision Inspection System Process

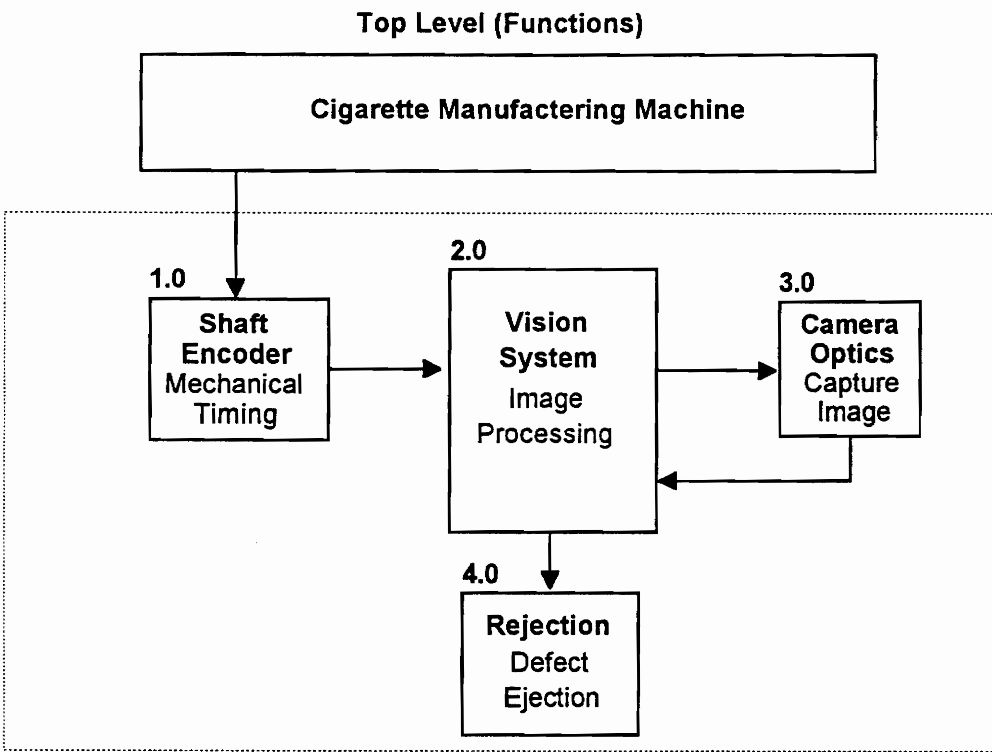


Figure 3.2: System Functional Flow Diagram

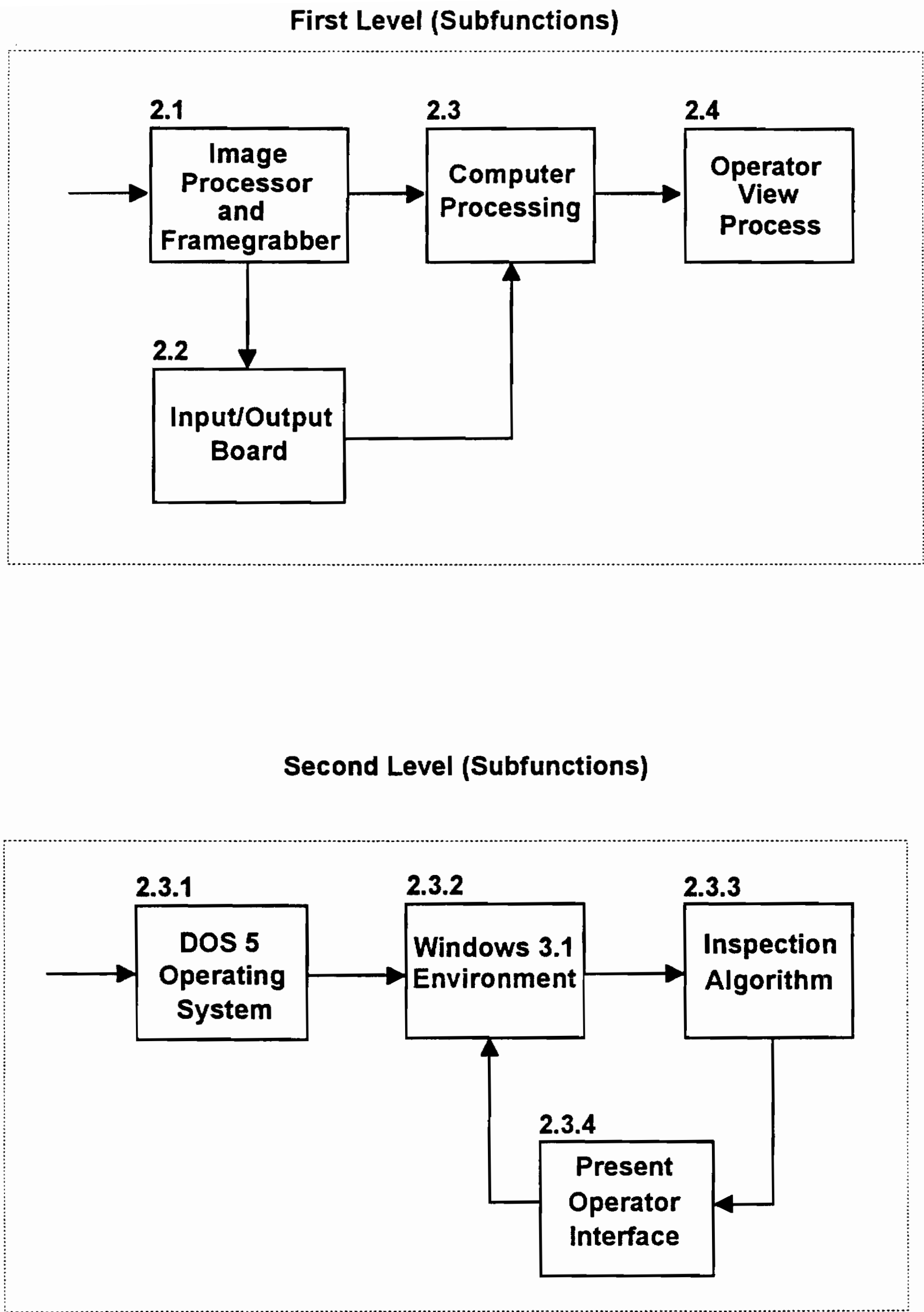


Figure 3.3: System Subfunctional Flow Diagram

Third Level (Subfunctions)

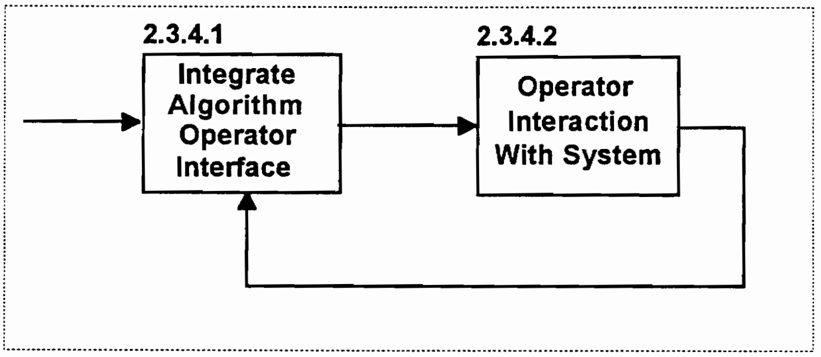


Figure 3.4: System Subfunctional Flow Diagram

The system has three primary operational requirements:

(1) To provide complete inspection of cigarettes at 10,000 ppm.

(2) To be capable of rejecting defective product.

(3) To provide human-machine interface and data collection.

The system will be auto starting to minimize the operators machine tasks. The system will not require the operator to manually interact with the system mode of operation. The human-machine interface or operator interface is there to provide the operator with information about their manufacturing process. The information is provided via tend chart to provide information-at-a-glance. Another useful function of the operator interface is that it allows the machine operator to visually check the inspection system. The operator can perform initial and periodic system diagnostics. For example, is the system on-line, is it acquiring an image, is the production data changing. Figure 3.4 illustrates the functional operational flow.

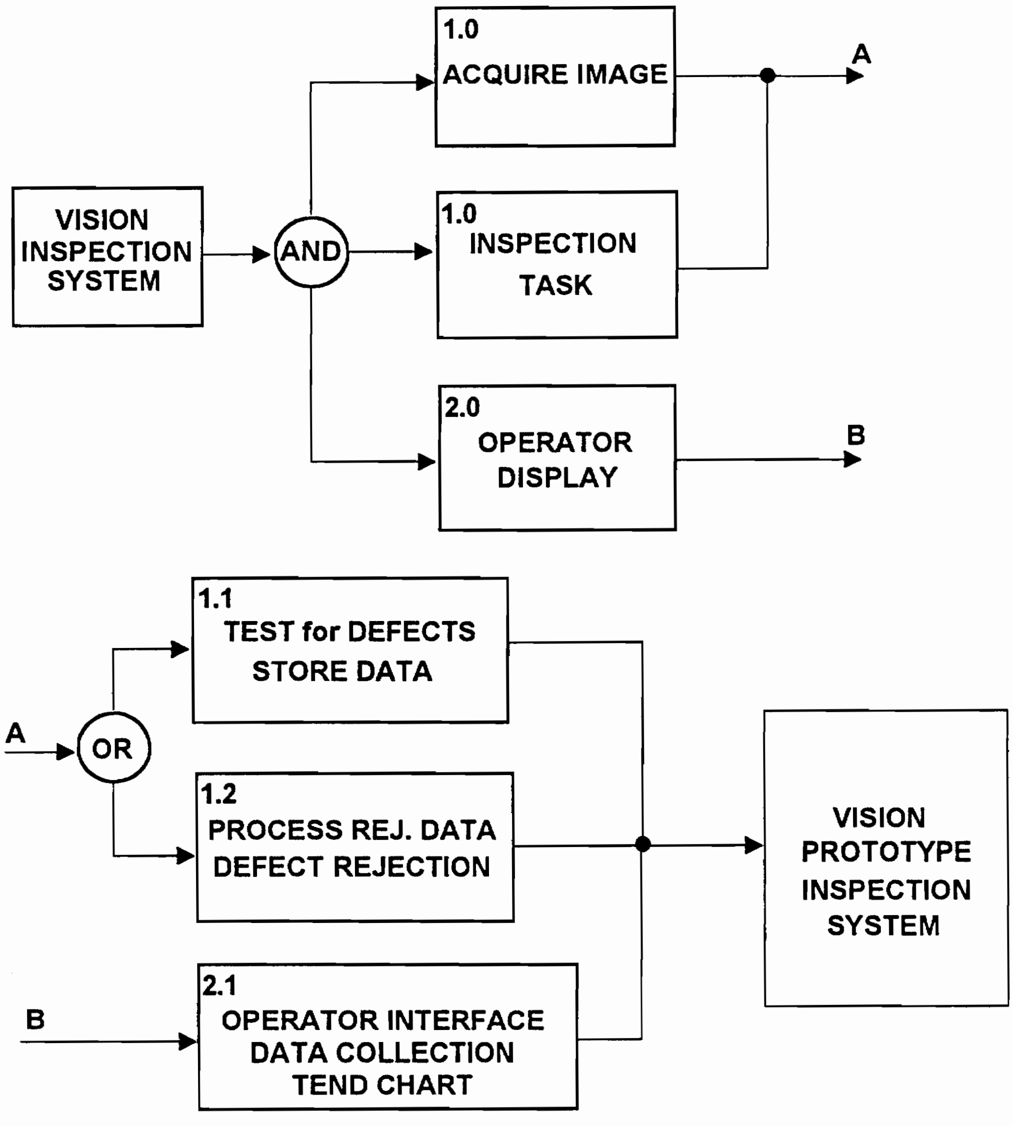


FIGURE 3.5: ORGANIZATIONAL FUNCTIONAL DIAGRAM

Maintenance functions will be provided by the development team at prototype installation. The cost to begin and support training on a prototype system would not be justifiable. Supporting the system at installation provides the design team with insight on operational personnel, manufacturing environment, manufacturing logistics, and overall system supportability.

The system functional flow and organizational functional diagrams were used to provide the design team with design criteria and constraints. The functional flow diagram depicts each functional component of the system and the organizational functional diagram depicts the system's process of inspection. The requirements allocation for a prototype system were defined as design parameters for each functional operation of the system. The functional system components design parameters are listed below:

(1) **Vision System**

Cost < $35,000

Processing Speed > 10,000 ppm

Screen Splitting Capability

NEMA 12

Operating Temp. > 50 C

Ao = 0.9998

MTBM = 1,000 Hr.

MMH/OH = 0.002

Skill Level = Design Engineer

Design Cost < $30,000

Mct = 1.5 Hr.(Max)

Failure Rate > .00033

(2) **Camera and Optics**

Cost < $10,000

Processing Speed > 10,000 ppm

Resettable Double Scan Rate

NEMA 12

Operating Temp. > 50 C

Ao = 0.9998

MTBM = 1000 Hr.

MMH/OH = 0.001

Skill Level = Design Engineer

Design/Purchase Cost < $3,000

Mct = 0.5 Hr.

Failure Rate = 0.001

(3) **Rejection System**

Cost < $10,000

Total Cycle > 10,000

Operating Speed 200 Hz.

Solenoid Input 24vDC

Max. Air Pressure 100 psi

Ao = 0.9998

MTBM = 225 Hr.

MMH/OH = 0.25 Hr.

Skill Level = Mechanical Designer

Design/Purchase Cost = $5,000

Mct = 0.5 Hr.

Failure Rate > .013

(4) **Shaft Encoder**

Cost < $2,000

NEMA 12

Voltage Input 24vDC

Optical Type

4 Channel Output

Skill Level = Electrical Designer

Failure Rate > 0.00025

The allocation or design parameter definition is to provide design constraints to give the designer guidelines and boundaries. System allocation decreases the amount of initial design time and cost. It also provides a monetary target for the development and design. The initial system allocation served as a starting and focus point for the design team.

A comparison between the original design and the optimized design is discussed in chapter IV. New design goals for the optimized version of the camera and optical design is included in chapter IV.

CHAPTER IV

DETAIL DESIGN AND DEVELOPMENT

A candidate application for machine vision technology generally involves both vision hardware and software as well as fixturing. For this project to be successful an established user/vendor relationship was a priority. The relationship has to be one of trust and dedication to the project. If prototype was successful then reproducing the system through the established user/vendor relationship would remove the resources provided by the design team. The design team would then be able to reach closure and begin a new project.

Most machine vendors possess image analysis, software, and computer expertise, with little experience machine control or design. Similarly, most machine control or design firms can handle fixturing and control but have little expertise in vision.

Integration of the vision inspection system with existing machinery is extremely important. The system could be successful in the lab and fail to perform on the manufacturing floor. A decision matrix was used in determining the vision system vendor [5]. The vendor decision matrix was used to evaluate three potential sources. The decision matrix served as a tool to help remove a large part of the subjectiveness. Finally, a machine vision vendor was chosen.

The system integration and associated equipment will be developed and designed by the design team. The design team consisted of two electrical engineers, an electrical designer, a mechanical engineer, and a mechanical designer. The manpower resource was minimized to restrain development cost.

4.1 Detail System Design

The vision process controller was developed by Pattern Processing Technologies. The vision processor is capable of speeds exceeding 10,000 ppm. The system employs direct contrast sensing techniques with a full line of software tools. To achieve the high speed imaging the vision system uses resettable partial scan camera technology. The partial scan camera technology enables the high speed frame capture rate. Each camera is assigned a predetermined number of scan lines through software configuration. The speed of the system is determined by the camera imaging speed and the image inspection processing speed.

The image speed of the system is calculated by :

$$(LS + N) \times HSR = IMAGING\ SPEED$$

$$(130 + 21) \times 31.7\ kHz. = 12{,}500\ ppm$$

Where: LS = Number Lines Scanned

N = Number Reset Lines

HSR = Horizontal Scan Rate

The processing speed is enhanced by the digital signal processing and split-screen imaging. The split-screen imaging allows multiple images to be displayed simultaneously. The complex high speed image processing and high resolution for successful inspection of cigarettes at manufacturing production rates.

The vision system is enclosed in a NEMA 12 enclosure. All cables are the quick disconnect type for exchangeability. The system can be quickly swapped with a spare with minimal downtime.

The Vision Program Manager software version 2.1 is used as the inspection tool. The software operates in a graphical environment. The tool selection is constructed from a group of icons. The icons form a graphical user interface for the end user. There is no requirement for programming on the system. The system interface can be performed through a touch screen interface mounted on the monitor. This greatly enhances the system acceptability in the manufacturing environment because normal skill levels can support and maintain the system.

Development of the optical camera assembly was done entirely by the design team. The camera was enclosed to seal it from dust and dirt. The camera enclosure incorporates a mirrored prism which divides the optical path in two distinct directions [8]. The camera optics provide two views of one cigarette. The two distinct optical paths are formed by two mirrors mounted at approximately a 45 degree angle to the prism. Each optical path is responsible for greater than 90 degree coverage of the cigarette rod. The two optical paths provide greater than 180 degree coverage per camera. The lens and optics are prealigned for easy installation and serviceability. An illustration of the camera, lens, and optical paths configuration is shown in figure 4.1.

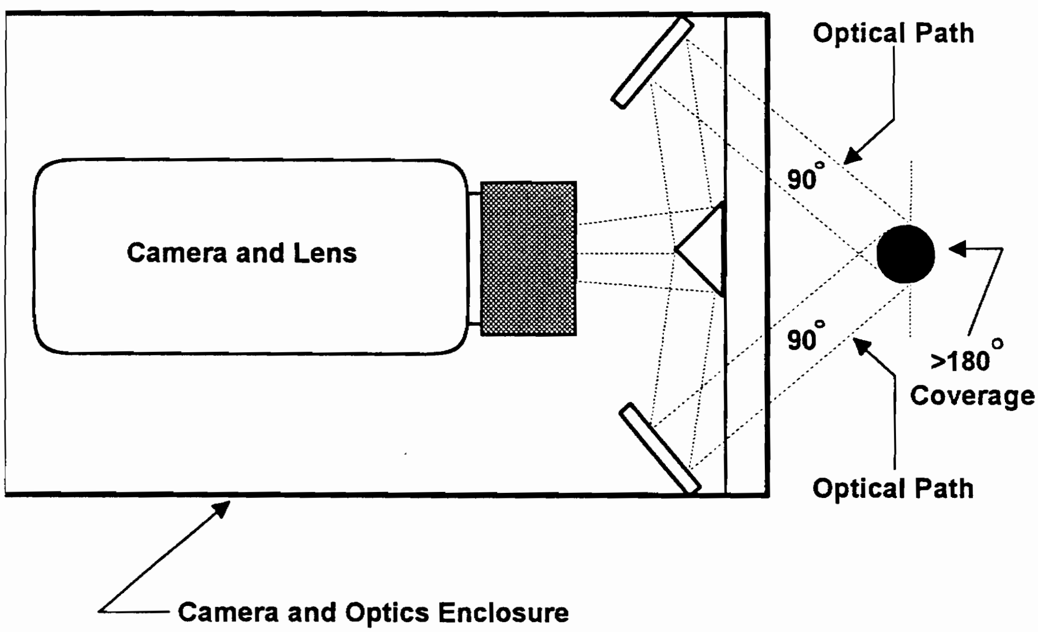


Figure 4.1: Camera Optical Design

The functional optical design was completed and modeled on a computer. The ray tracing of the optical paths appeared to be a viable design platform. In appendix A, figure A.1 is the computer model of the camera and optical assembly.

Adequate lighting was required for the camera and optics to receive a high quality image. Using a strobe to provide intermittent light source produced two advantages. The strobe provided direct high intensity light so the aperture of the camera could be closed. Closing the aperture of the camera prohibited any ambient light from being imaged. The strobing action also stopped the mechanical movement of the machine for image acquisition. Fiber-optic light guides were used to transmit the light from the strobe to the camera. The fiber-optics were formed into two line fiber arrays 0.030 thousandths thick and 100 millimeters in length. The line fibers were mounted on the top and bottom of the front of the camera enclosure. The light path was to follow the same angle of projection as the optical path. The line fiber was to provide a line illumination for the entire length of the cigarette rod. The lighting design was superimposed on the camera and optic model. This completed the camera imaging model. Figure A.2

in appendix A is an illustration of the computer design model mounted on the front of the camera enclosure.

The computer model was for functional design analysis. The model provided the design team with design criteria and parameters to work from and optimize worse case scenarios.

The optical enclosure was a critical portion of the design. This assembly would be installed directly on the machine and would require indirect interaction with the operator. The need for design optimization on the optical enclosure for system acceptability was a high priority [2].

The systems engineering process was reapplied to the computer model design for reliability, maintainability, ergonomics, productibility, supportability, and economic feasibility. A conceptual design review was performed on the optical assembly to evaluate engineering considerations that would effect the overall system functionality. The reliability and maintainability of the model was closely related. Improvement was necessary before the optical assembly could be supported. The optical assembly has six different adjustments that required a qualified individual to calibrate. These adjustments were used to align the optics and adjust the image position. The assembly also incorporated a 60 lb/sq.in. spring that was used to stabilize and provide rigidity the camera fixture. To decrease the maintainability and increase the reliability of the assembly. The adjustments were removed from the optical arrangement. All of the optical components were fixed and machined for precision assembly. Eliminating the adjustments in the optics the camera would have to provide some vertical adjustment to allow for image positioning on the camera sensor. Image positioning is accomplished by the projection of an image on the CCD (charged coupled device) array, the camera sensor. Simultaneous image projection on the video monitor would be the result of acquiring all the images at the same instant in time. This would reduce the number of times the vision system would have to update the screen.

The camera was removed from the optical enclosure and mounted outside of the assembly. To maintain lens focusing and aperture adjustments the camera lens was divorced from the camera body fixing the focus and aperture adjustments. The need for vertical movement of the camera sensor was still required. The new camera fixture was designed with a dovetail to provide precision movement in the desired direction. A removable micrometer was used to position the camera fixture with respect to the optical assembly.

Figures A.4 and A.5 in Appendix A illustrate the design optimization of the optical assembly and camera fixture.

Constantly reviewing the economic feasibility of the design optimization provided the opportunity to redesign the lighting concept. The fiber-optic line array assembly was eliminated and the fiber-optic illuminators were mounted internally in the optical assembly. An additional set of fiber-optic illuminator widows was used to reduce the bundle diameter of the fiber-optic bundle. This completely eliminated one assembly, reduced the diameter of the fiber-optic bundle, and the associated costs.

The design optimization accomplished a 50% reduction in overall size and weight. The manability [2] of the system was increased by eliminating the need for calibration and reduction in size. The assembly did not present an obstacle for the operator's normal tasks. Minimizing the impact of the system on the operating personnel the acceptability of the system will be increased.

The requirements allocation to optimize the prototype system were defined as design parameters for each functional operation of the system. The functional system components design parameters are listed below:

(1) **Vision System** **(Not Revised)**

Cost < $35,000

Processing Speed > 10,000 ppm

Screen Splitting Capability

NEMA 12

Operating Temp. > 50 C

Ao = 0.9998

MTBM = 1,000 Hr.

MMH/OH = 0.002

Skill Level = Design Engineer

Design/Purchase Cost < $30,000

Mct = 1.5 Hr.(Max)

Failure Rate > .00033

(2) **Camera and Optics (Revised)**

Cost < $5,000

Processing Speed > 12,500 ppm

%50 Reduction Size

Fixed Adjustments

Utilize Investment Casting

Resettable Double Scan Rate

NEMA 12

Operating Temp. > 50 C

Ao = 0.9999

MTBM = 1,500 Hr.

MMH/OH = 0.0008

Skill Level = Design Engineer

Design Cost < $10,000

Mct = 0.25 Hr.

Failure Rate = 0.001

(3) **Rejection System** **(Revised)**

Cost < $10,000

Total Cycle > 10,000

Operating Speed 200 Hz.

Solenoid Input 24vDC

Max. Air Pressure 100 psi

Stability Increased

Ao = 0.9998

MTBM = 250 Hr.

MMH/OH = 0.25 Hr.

Skill Level = Mechanical Designer

Design Cost = $3,000

Mct = 0.5 Hr.

Failure Rate > .015

(4) **Shaft Encoder** **(Not Revised)**

Cost < $2,000

NEMA 12

Voltage Input 24vDC

Optical Type

4 Channel Output

Skill Level = Electrical Designer

Failure Rate > 0.00025

The allocation or design parameter definition is to provide design constraints to give the designer guidelines and boundaries to correct design deficiencies. This is the objective of the design optimization phase.

Designing for producibility was a consideration in the design optimization. The optical assembly components could be fabricated from investment casting lowering the cost and providing a single source supplier for the entire assembly.

Providing resources to supply the end product was a consideration that evaluated through each design phase. The system had to be reliable in both operation and in future system procurement.

The mechanical rejection assembly is comprised of two drums and their valves. The design required the modification of existing equipment on the machine. As the cigarette is rotated around the vacuum drum a short blast of air is applied to the transfer flute of the sequential drum.

The transfer of the defective cigarette is inhibited. The defective cigarette maintains its position on the drum by being recaptured by the vacuum after the transfer flute has rotated out of position. As the drum continues to advance the defective cigarettes position themselves. The rejection pan strips the defective cigarette off of the drum. The cigarette free falls into the rejection pan. The rejection pan has a positive pressure applied to the front of the pan to force the cigarettes out of the rejection pan and into the rejection bins. The positive air pressure insures that defective cigarettes will not build up in the rejection pan and cause the machine to jam.

In the design optimization of the rejection system it was decided that by increasing the width of the drums by 20 millimeters would increase the stability of the cigarette during transfer and rejection capture. The vacuum holes in the drums were elongated to provide more surface area of the cigarette to be exposed to vacuum ports. This provided an increase in the stability of the cigarette rotation and inspection.

A shaft encoder was used to establish the mechanical timing between the vision system and the existing machine. The encoder was to be installed in the existing timing wheel area of the machine. Access to the shaft encoder would be provided through existing maintenance covers. The shaft encoder is to be driven by a pulley mounted to the existing timing pulse wheel on the machine. The output of the encoder has three channels, a 24 cigarette pulse, 120 sub-cigarette pulse, and a single pulse per revolution of the encoder shaft. The 24 cigarette pulse triggers the vision system to acquire an image at the precise intervals. Both cameras acquire images simultaneously. The 120 sub-cigarette pulse was designed into the system to provide an on-off function for the rejection solenoid. The 120 sub-cigarette pulse allows five time intervals within each cigarette flute to energize and de-energize a solenoid. Due to the speed of the equipment it was decided that removing a single cigarette at 10,000 ppm could be a problem. The design should posses the capability of powering a device on and powering it off. Figure A.3 in appendix A illustrates the mechanical rejection assembly. Figure 4.2 illustrates the pulse train output from the shaft encoder.

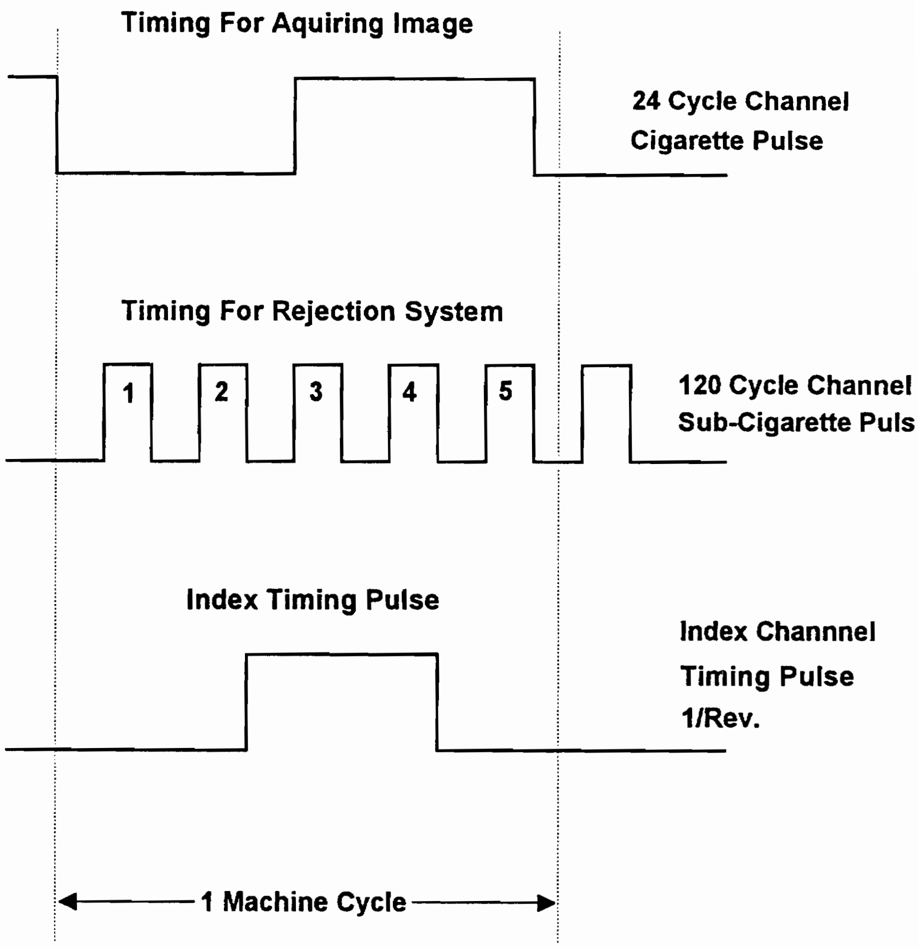


Figure 4.2: Shaft Encoder Output Pulses

The operator interface is provided by the touch screen video monitor. The touch screen allows the user to activate various controls by using a visual representation of the process as they interact with the system. The video monitor displays an inspected image in real-time. The cigarette rod is displayed. If a defect occurs on the rod the video image will be frozen for three seconds. The defective region of the cigarette rod will be outlined with a red bounding box around the defect. This provides the operator time to visualize and understand the defective region. While the video image is frozen, the inspection process is ongoing although the video image will not be updated until the existing defective region has timed out.

A human-machine interface is used to interact between the vision inspection system and the operator. This provides for a more flexible and graphical representation of the process. The interface is totally customizable to the needs of the manufacturing environment. The system is also capable of supporting a statistical process control charts to allow the operator an increased level of process awareness. Figure 4.3 illustrates the vision inspection system interface screen.

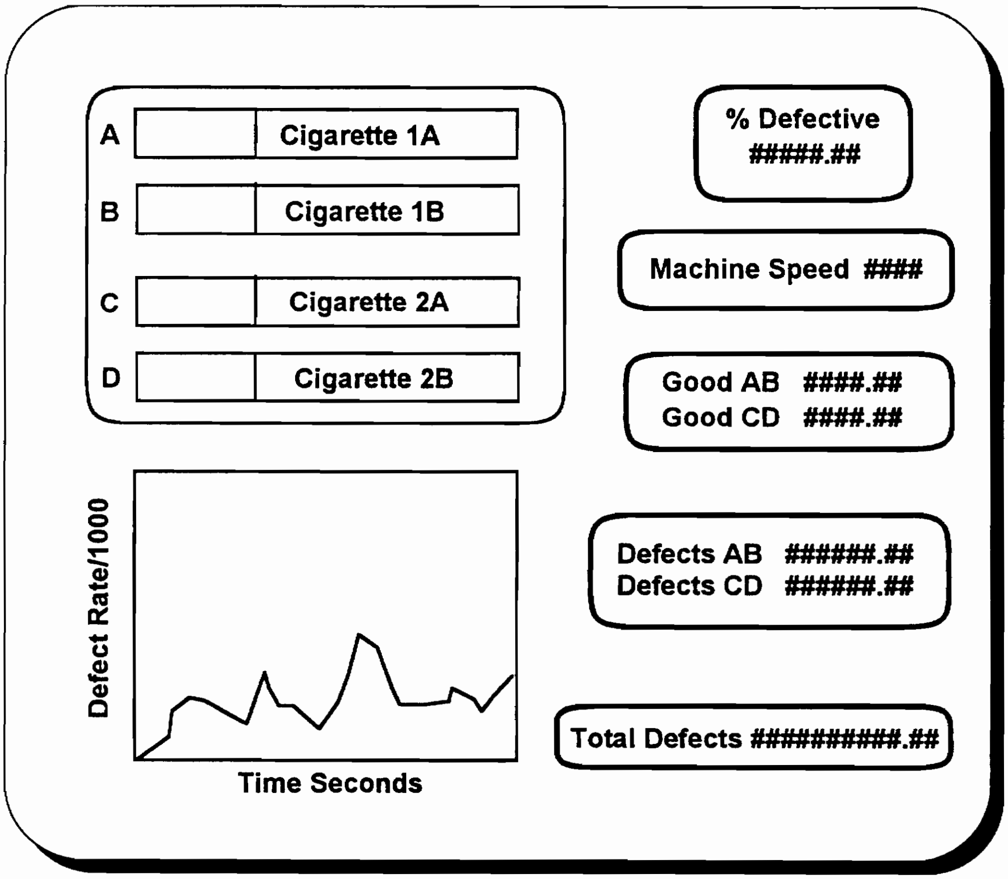


Figure 4.3: Vision Inspection System Interface Screen

The vision inspection system interface screen displays four cigarette images. Two cameras are mounted on the machine to provide the 360 degree coverage. Each camera has two optical paths, 90 degrees each. Referring to figure 4.3, cigarette images 1A and 1B are associated with camera one. Cigarette 2A and 2B are associated with camera two. The graph on the interface screen trends the number of defects per thousand. This provides the operator with real-time process information. The data displays are data collection counts regarding the inspection task. The data collection counts update dynamically in real-time.

4.2 System Installation

The systems engineering process was reapplied during the installation of the prototype system in the factory. All the installation procedures were documented. The documentation would be used later to develop templates for drilling, and drawings for guard modifications. If the system was successful in its test and evaluation the optimization of the installation and implementation would be performed in the preliminary system design of the nest phase of the project.

4.3 System Documentation

The preparation of the system documentation was an ongoing process. The was organized from initial conceptual layouts, from the layouts the detail drawing were made for fabrication of the assemble parts. Assembly drawings were constructed from the detail drawings. This process provided the design team with accurate tolerencing and proper fits. Installations procedures and an operational manual was created to provide system support at installation. The documentation also served as a model for the factory to evaluate for supportability. A spare parts list with recommended quantities was not done for the prototype system. The system evaluation and testing would be supported with the standby system.

Providing accurate and precise documentation helps ensures that fabrication costs should be within the estimates. Photographs were also taken to be used for further evaluation if the systems was to be reproduced and installed throughout the factory.

4.4 System Prototype Test and Evaluation

The system testing in the vision laboratory was done in static condition. This did not provide the design team with any data on how the inspection system would perform when it was installed. The availability of a test machine was not an option in the beginning of the project.

The objectives for the evaluation was to determine the overall effectiveness of the system in removing identified defects from the product flow. The system had to inspect and identify the correct defective cigarette and verify that the correct one was rejected. The sensitivity of the system relative to critical cigarette defects needed to be determined. Listed below is an integrated test and evaluation plan:

Background

The vision inspection system utilizes a two cameras and folded mirror optics to inspect 360 degrees of the entire cigarette, and identify color contrast that represent defects. Inspection can be accomplished during normal operation, at rates up to 10,000 cigarettes per minute. Since both the cigarette rod and filter are inspected together, a significant impact on quality is expected.

Vision Inspection System Test and Evaluation Plan

Objectives:

(1) Determine the impact expected from the vision inspection system relative to cigarette quality and waste.

(2) Identify those defects that will be identified and removed from the product flow by the vision inspection system.

(3) Verify that the correct cigarette is rejected once identified as critically defective.

(4) Determine the sensitivity of the vision inspection system relative to those critical defects identified and rejected.

(5) Determine vision inspection system efficiency.

(6) Identify any specific manufacturing practices that must be modified in order to optimize the performance of the vision inspection system.

(7) Identify work classifications and changes to daily work activities necessary to support operation and maintenance of the vision inspection system.

(8) Document any training requirements necessary

to support the vision inspection system.

Test Plan:

Force feeding defect is not feasible. All testing conducted must be performed with the maker in normal operation.

(1) An initial baseline will be established with the existing detection system operational. Both quality and waste information will be generated during this period.

(2) The next phase of the testing will be conducted with the vision inspection system operational.

(3) Steady state operating conditions are to be evaluated for the baseline and phase 1.

(4) Sample sizes for each test condition will be approximately 12,000 cigarettes per condition. Steady state condition replication 6,000 with more replications.

Audit Methodology:

The sensitivity of the vision inspection system will be assessed by auditing all samples and rejects using factory audit criteria. By auditing samples and rejects, the sensitivity of the vision inspection system to identify specific defects can be measured. Determining a sensitivity threshold for vision detectable defects will aid in quantifying the potential this system has for improving cigarette quality on particular brands.

Baseline:

The control portion of this evaluation will be conducted with the vision system installed but disabled. The purpose will be to generate a process baseline relative to the fraction nonconforming cigarettes manufactured by that machine. Additionally, total cigarette production and waste quantities will be determined per shift to establish a total waste baseline. All existing inspection systems will be operational during this time.

Phase 1:

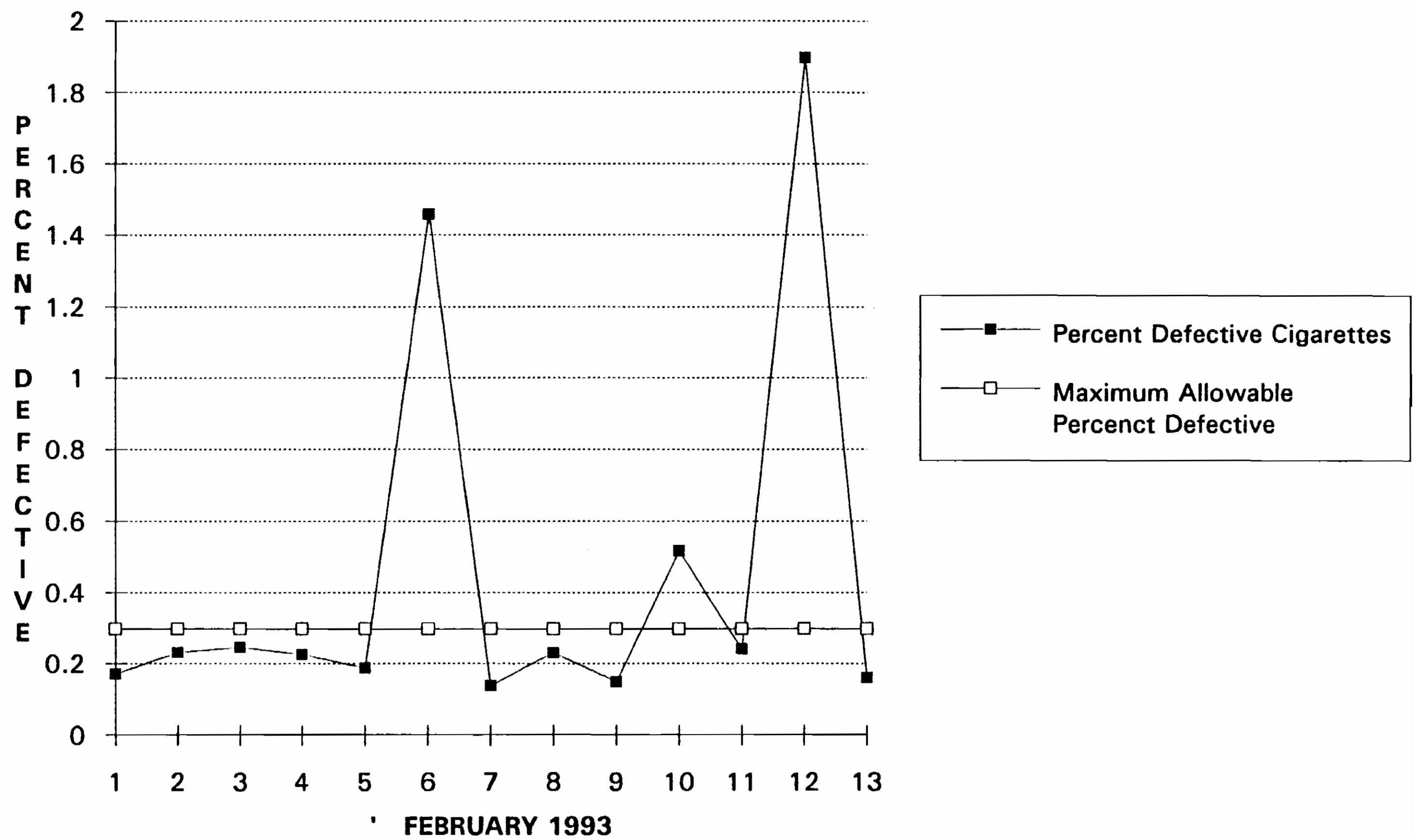
Phase 1 testing will duplicate the conditions executed during the control phase. However, Existing detection systems will be turned off to access the capability of the vision inspection system with no other optical scanning taking place. Finished cigarettes will be audited for defect rates. Additional information will be gathered relative to the specific defects identified by the vision inspection system and the efficiency with which they are removed. End of shift waste and production quantities will be captured in order to complete a mass balance. Since the vision inspection system has the capability to count all cigarettes it rejects from the product flow, this number will be used to confirm what was collected form the rejection bins.

The baseline on the machine was performed mid January. the test and evaluation of the vision inspection system was performed first of February. The test was perform over a thirteen day period. The results from the preliminary test demonstrated that the vision system was successful in reducing the maximum allowable percent defects. The results demonstrated that the system was effective ten out of the thirteen days for an efficiency of 77%. Table 4.1 is a tabular list of the test results. Figure 4.4 is the Vision Inspection System audit summary. The audit summary illustrates that the maximum allowable percent defective rate is 0.3%.

Date	Shift	Total Number of Cigts	Total Number of Acceptable Cigts	Total Number of Defective Cigts	Percent Defective Cigarettes	Maximum Allowable Percenct Defective	Difference
2/1/93	A	1581850	1579147	2703	.171	0.30	0.13
2/2/93	A	688247	686658	1589	.231	0.30	0.07
2/3/93	A	813242	811232	2010	.247	0.30	0.05
2/4/93	A	1035604	1033263	2341	.226	0.30	0.07
2/5/93	A	1156597	1154419	2178	.188	0.30	0.11
2/6/93	A	746468	735594	10874	1.457	0.30	-1.16
2/7/93	A	1221136	1219453	1683	.138	0.30	0.16
2/8/93	A	1129044	1126431	2613	.231	0.30	0.07
2/9/93	A	319652	319175	477	.149	0.30	0.15
2/10/93	A	518221	515546	2675	.516	0.30	-0.22
2/11/93	A	779831	777937	1894	.243	0.30	0.06
2/12/93	A	117155	114931	2224	1.898	0.30	-1.60
2/13/93	A	807570	806276	1294	.160	0.30	0.14
TOTAL		10914617	10880062	34555	.317		
Average		839586	836928	2658	.450		-.150

Table 4.1: System Prototype Test and Evaluation Data

Figure 4.4: Vision System Audit Summary



CHAPTER V

LIFE-CYCLE COST ANALYSIS

Calculation of the life-cycle cost(LCC) refer to the cost encountered during the design and development phases of the prototype system. These phases include concept, preliminary design, detail design, fabrication, implementation, test and evaluation, and system retirement. A Life-Cycle Cost analysis is the analytical analysis of the expected cost of a project [2]. An advantage of the life-cycle cost analysis technique is that it may be applied to any phase or phases of the life-cycle process. All of the expected costs can be displayed in a cost breakdown structure.

The total system cost is the summation of the research and development costs, Production and construction costs, operation and maintenance costs, and disposal costs.

$$Cr + Cp + Co + Cd = C$$

Where: Cr = Research and Development Costs
Cp = Production and Construction Costs
Co = Operation and Maintenance Costs
Cd = System Disposal Costs

All of the expected costs are displayed in a cost break down structure. Figure 5.1 illustrates the cost break down structure for the vision prototype inspection system.

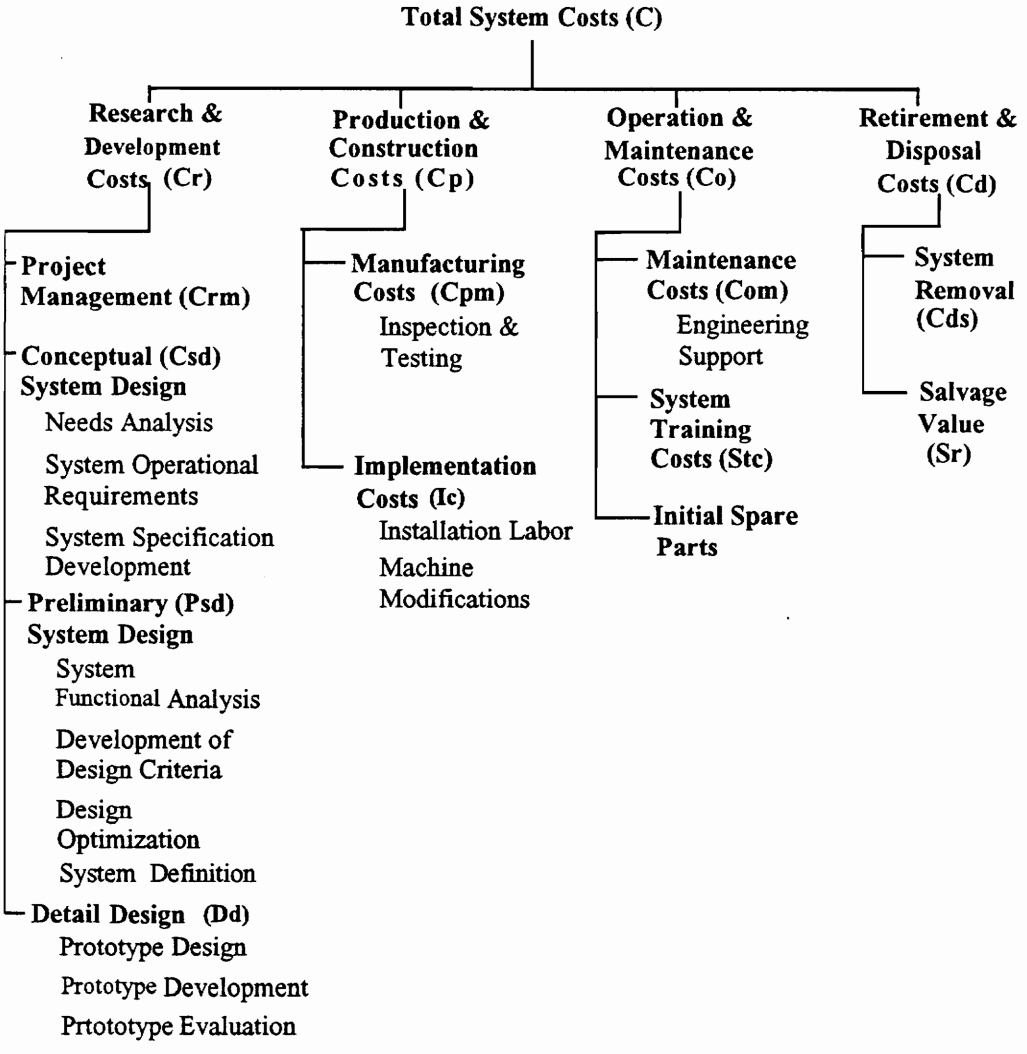


Figure 5.1: Prototype Cost Breakdown Structure

The research and development costs (Cr) includes all of the design and development costs associated with designing and fabricating one prototype system. The research and development costs include Project Management (Cr), Conceptual System Design (Csd), Preliminary System Design (Psd), Detail Design (Dd).

$$Cr = Crm + Csd + Psd + Dd$$

Production and construction costs (Cp) include Manufacturing Costs (Cpm), Implementation Costs (Ic). Manufacturing costs includes inspection and testing and initial spare parts.

$$Cp = Cpm + Ic$$

Operation and maintenance costs (Co) include the Maintenance Costs (Com) and System Training Costs (Stc).

$$Co = Com + Stc$$

The Retirement and Disposal Costs (Cd) include the System Removal Costs and Salvage Costs (Sr).

$$Cd = Cds - Sr$$

Since the project management cost (Crm) is a fixed salary cost and the equipment utilized is not included in the expense of a project the project management costs (Crm) are not considered.

The research and development costs are associated with conceptual system design (Csd). The conceptual system design cost is \$8,000. This cost can be attributed to seed money to determine the feasibility of the project. The preliminary design Costs (Psd) is \$40,000. This expense included the purchasing of the vision system. Shipment of the system was included in the vendor's purchase price. The detail system design costs (Dd) is \$51,500. This expense included detail fabrication and design of the prototype assemblies including documentation.

Production and construction costs (Cp) include the Manufacturing Costs (Cpm) and Implementation Costs (Ic). The inspection and Testing cost of the system is estimated at \$13,614.62. The manufacturing labor to inspect the product samples is \$3,607.50. The labor is calculated by dollar rate per hour including dollar rate for benefits multiplied by the 13 day test period.

$$(\$12/Hr + \$25/Hr_{(Benefits)}) * 7.5Hr. = \$277.50$$

$$\$277.50/day * 13\ days = \$3607.50$$

The production charge for the tobacco waste during the test was \$10,914.62. This is calculated by the total number of cigarettes inspected multiplied by \$.001.

The Implementation Costs (Ic) is calculated from the labor charged to install the prototype system in the manufacturing facility. This Expense is \$1,380.00. The installation required 4 man-days at a labor rate of $345.00 per man-day. The machine modification costs are included as labor cost for one machinist for 2 man-days at $345.00 per-man day. The machine modification cost is $690.00. Total implementation costs are $1,380.00 for the installation of the system.

The Operation and maintenance Costs (Co) Totaled $61,600. The Maintenance Costs (Com) is calculated from the engineering support costs during production. Three engineering technicians provided three shift coverage on the system for four weeks. The cost of the engineering support is $21,600.00. The initial spare parts for the system costs $40,000.00.

The System Training Costs (Stc) is determined by the training cost associated with training six technicians for one week. The cost per technician is $1,725/week. The total cost of the training is $10,350.00.

The Retirement and Disposal (Cd) costs equal the cost to remove the system only. There is no salvage value of the system under the current management development policies.

Figure 5.2 illustrates the life-cycle cost summary.

Table 5.1: Life-Cycle Cost Summary

COST CATEGORY	COSTS ($)	% CONTRIBUTION
1. Research & Dev. (Cr)	99,500	52.59
a. Conceptual System Design (Csd)	8,000	8.04
b. Preliminary System Design (Psd)	40,000	40.2
c. Detail System Design (Dd)	51,500	51.75
2. Production and Const. Costs (Cp)	15,684.62	8.28
a. Manufacturing Costs (Cpm)	13,614.62	86.8
b. Implementation Costs (Ic)	2,070	13.2
3. Operation & Maintenance Costs (Co)	71,950	38.23
a. Maintenance Costs (Com)	21,600	30
b. Initial Spare Parts	40,000	55.6
c. System Training (Stc)	10,350	14.38
4. Retirement & Disposal Costs (Cd)	2,070	1.08
a. Salvage Value (Sr)	0	0
GRAND TOTAL (C)	$376339.24	100

CHAPTER VI

SUMMARY

The Vision Inspection System is a integrated inspection system. It incorporates a high speed inspection algorithm with a visual indication of the process. This technology has a large impact on manufacturing support resources.

This project was based on the systems engineering approach to development and design of a prototype system. The systems engineering process provided the development team and the design team with organizational and project management techniques. It provided a systematic approach that integrated the manufacturing requirements of the system with the scientific parameters of the project.

The systems approach provided the techniques and structure to determine the life-cycle cost of the prototype system. The life-cycle cost analysis performed on the prototype system will be utilized in determining the economic feasibility of building and/or installing multiple vision inspection systems in a manufacturing facility. The total cost of the system is $189,204.62.

Applying the Systems theory to the individual project components provided problem solving techniques that otherwise may have been an oversight. Using the systems engineering process as a model to effectively evaluate each portion of the design against provided to be an effective means for reaching closure of the prototype. Closure was meet economically and timely.

CHAPTER VII

CONCLUSIONS AND RECOMMENDATIONS

The Vision Inspection System prototype has demonstrated an alternative technology for integrated inspection system in the manufacturing environment. The inspection capability of the system inspect 71% of the identifiable cigarette defects. The system also decreased the percentage defective packs by 75%. The system demonstrated that it could effectively detect and reject defective cigarettes with an overall efficiency of 77%. The system provided the operator with dynamic manufacturing information that can be utilized to increase the efficiency of the manufacturing complex.

This technology has many advantages over a traditional discrete inspection systems. The prototype system demonstrated that the an basic level of process control can be integrated into the machine operator's environment. This form of inspection integration is very important with high rates of manufacturing. Three patent applications were submitted for the vision inspection system. Patents were submitted for optically inspecting cylindrical surfaces, fluted drum optical inspection application, and optical arrangement for inspecting substantially circular objects.

The inspection systems impact on the manufacturing environment could be very costly in terms of supportibility and maintainability. Training cost for manufacturing personnel could exceed economic justification of the system.

Employing the systems engineering process to develop the prototype system proved to be invaluable in the design optimization phase and the assembly integration. The systems engineering process allowed the development team the ability to provide the design team with clear direction and objectives regarding the system design. Using the systems approach as a model provided the project with mapping process that successfully designed and developed a prototype system that exceeded its original design objectives.

A subsequent project has been recommended to further evaluate the impact of this technology on the manufacturing environment. Additional testing of the system will be required to measure its full capability.

The life cycle cost of the system can be accurately formulated with the data obtained from the prototype system. Computing the life cycle cost based on a factory implementation schedule would provide necessary information in the decision process whether to continue the development of the technology for the cigarette manufacturing industry.

Future areas of research should be directed in increasing the overall efficiency of the system. Vision technology is a viable means to increase the quality and process feedback. Further research should be concentrated in closing the feedback loop for self-learning image analysis algorithms incorporating neural network technology.

A complete analysis utilizing modeling techniques should be developed to model manufacturing technologies and how they impact the manufacturing environment.

APPENDIX A

VISION INSPECTION SYSTEM PROTOTYPE DESIGN

Pages 71 - 80 are detail designs of the camera and optical assemblies. The optical image ray tracing design is shown to demonstrate and support the imaging process.

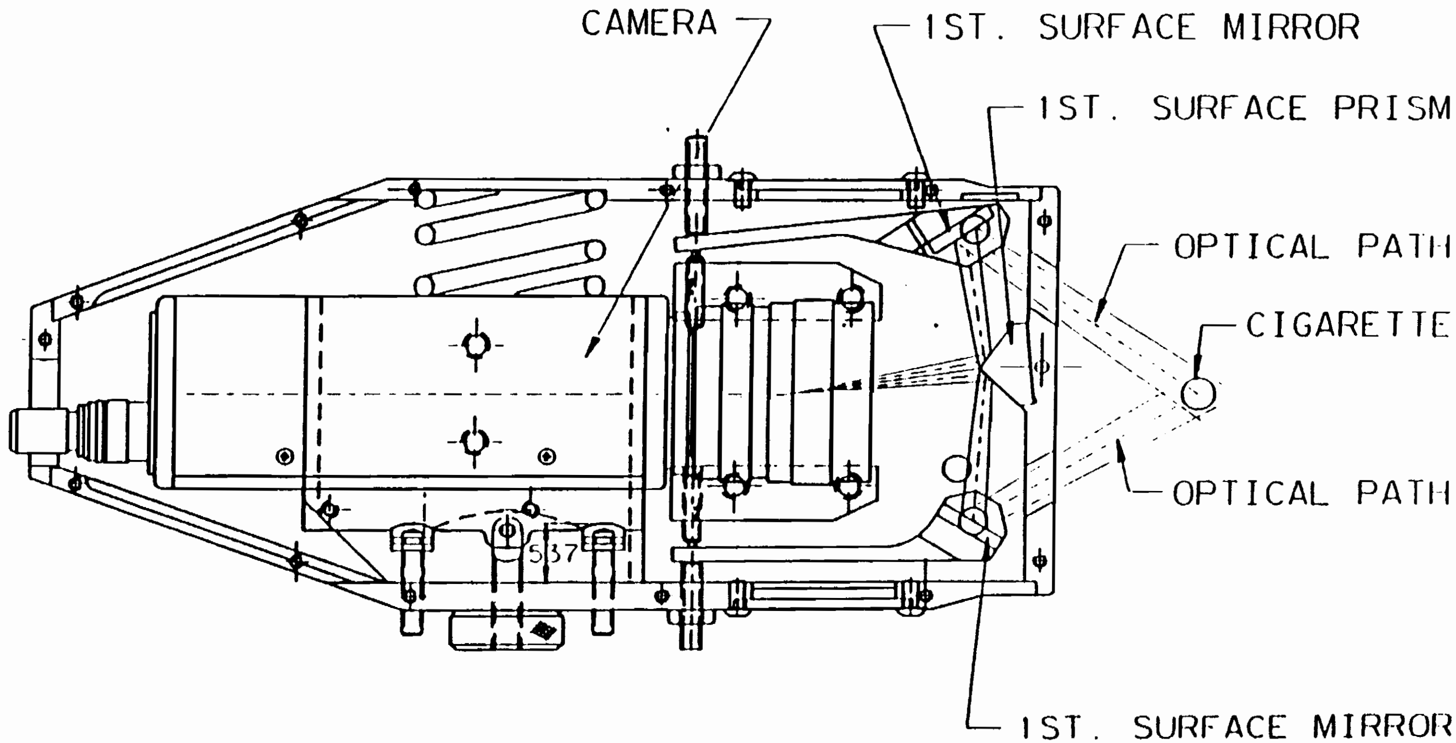


Figure A.1 Camera and Optical Assembly Model

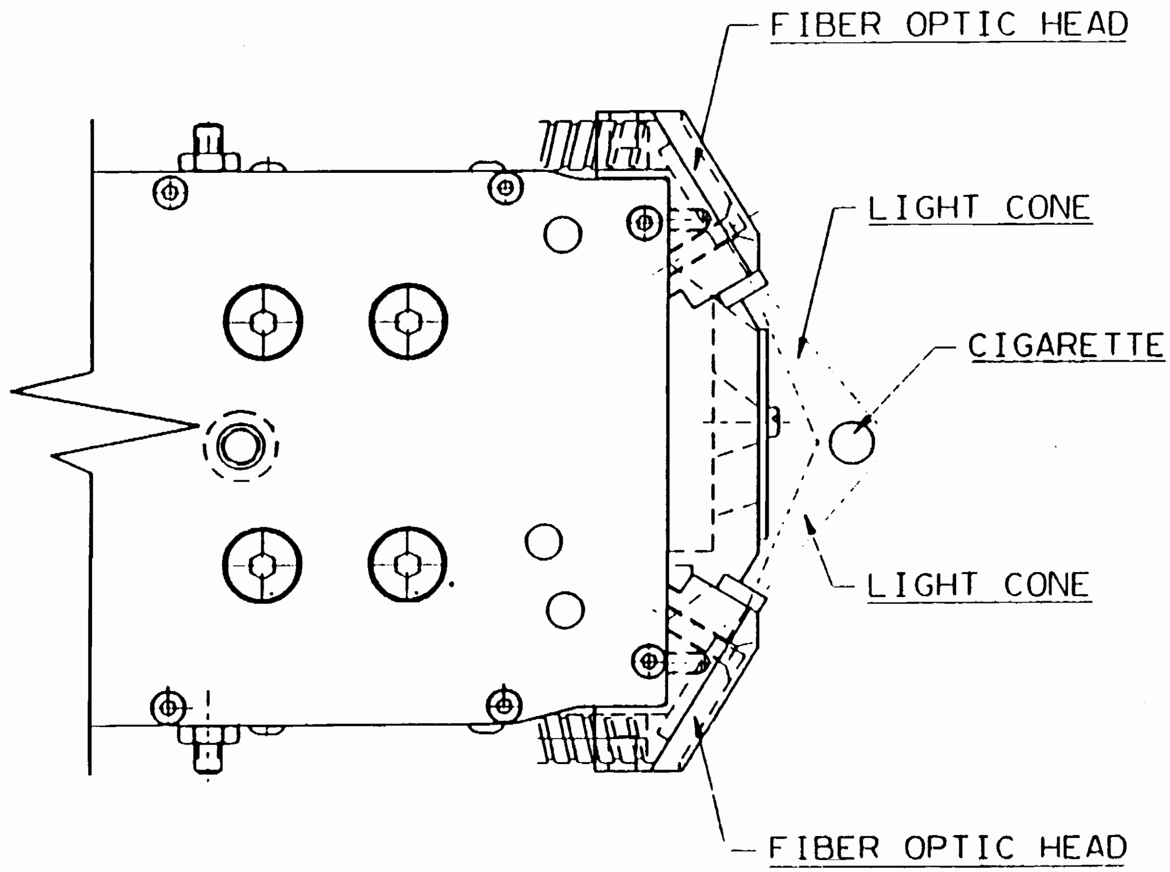


Figure A.2: Fiber-optic Lighting Mounted on Optical Assembly Model

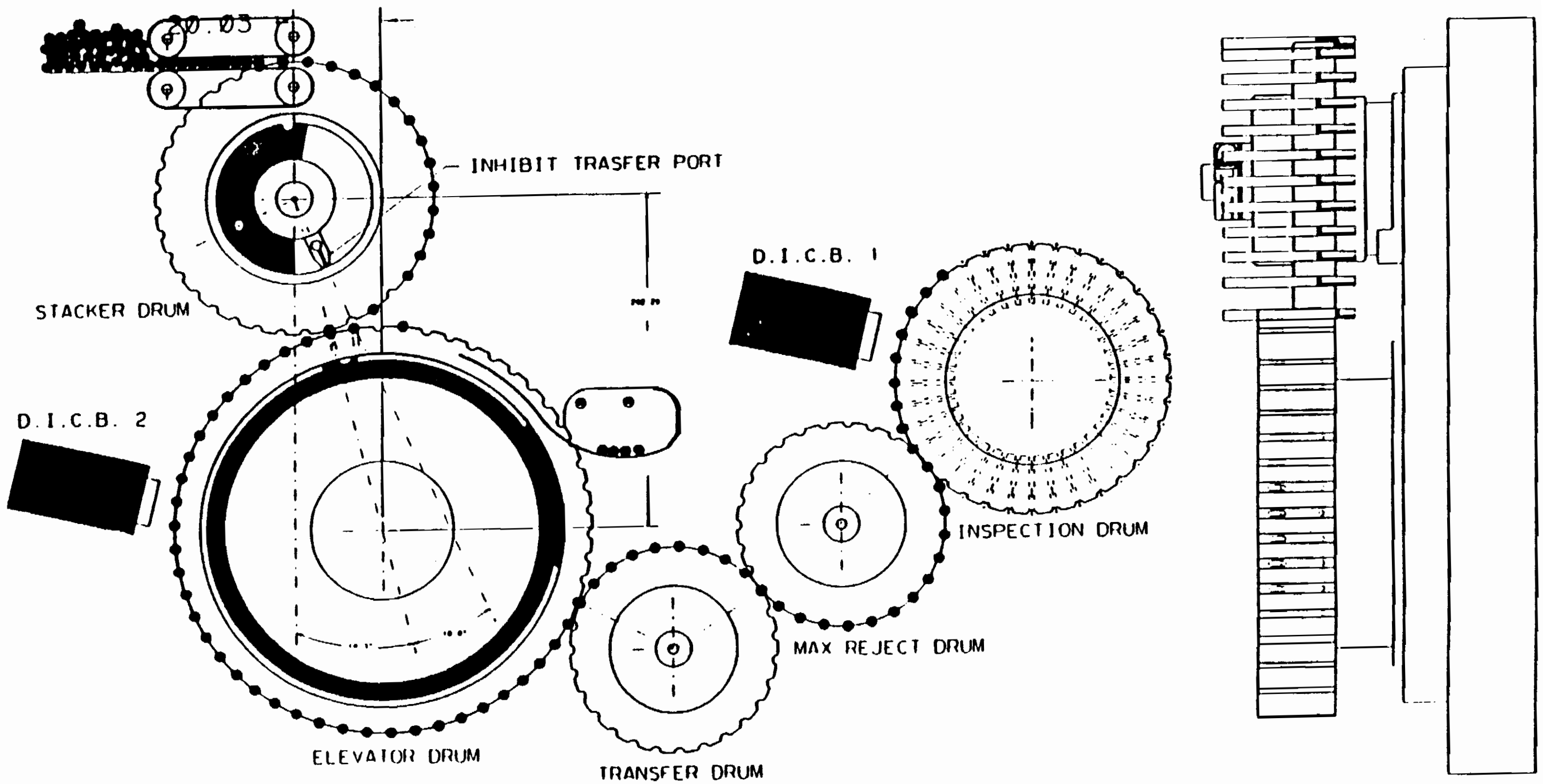


Figure A.3: Mechanical Rejection Assembly

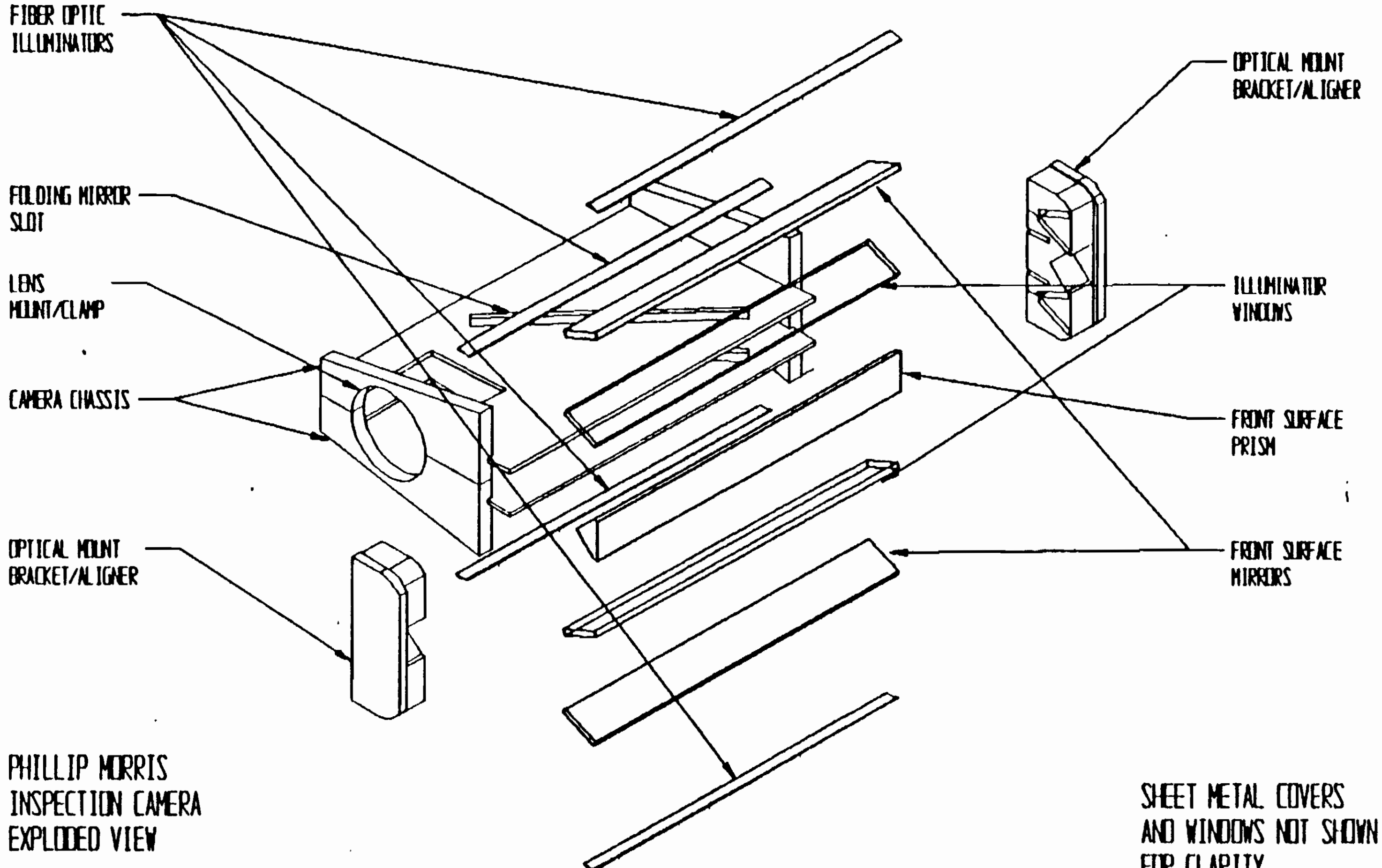


Figure A.4: Optical Assembly Design

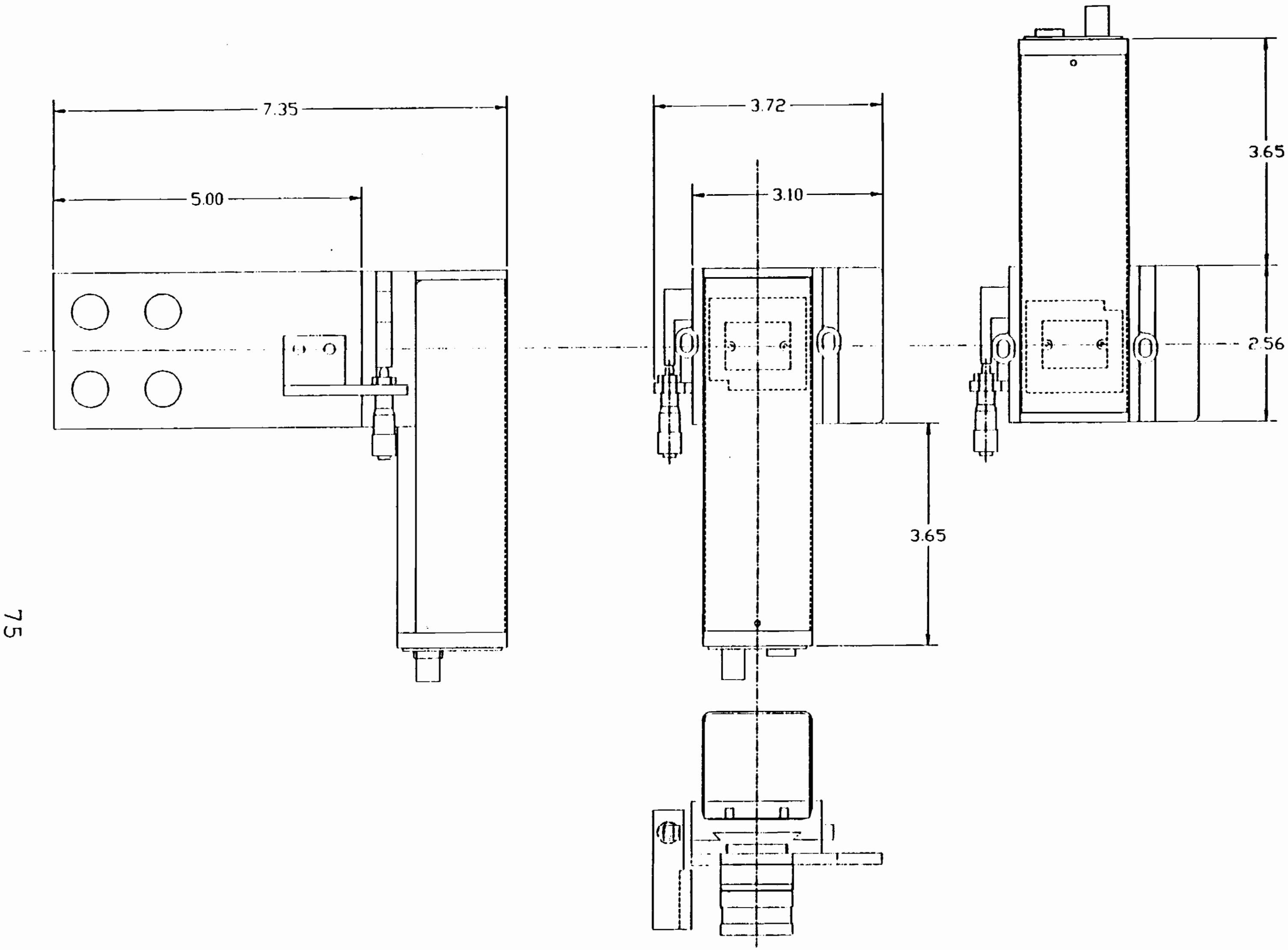


Figure A.5: Camera Fixture Design

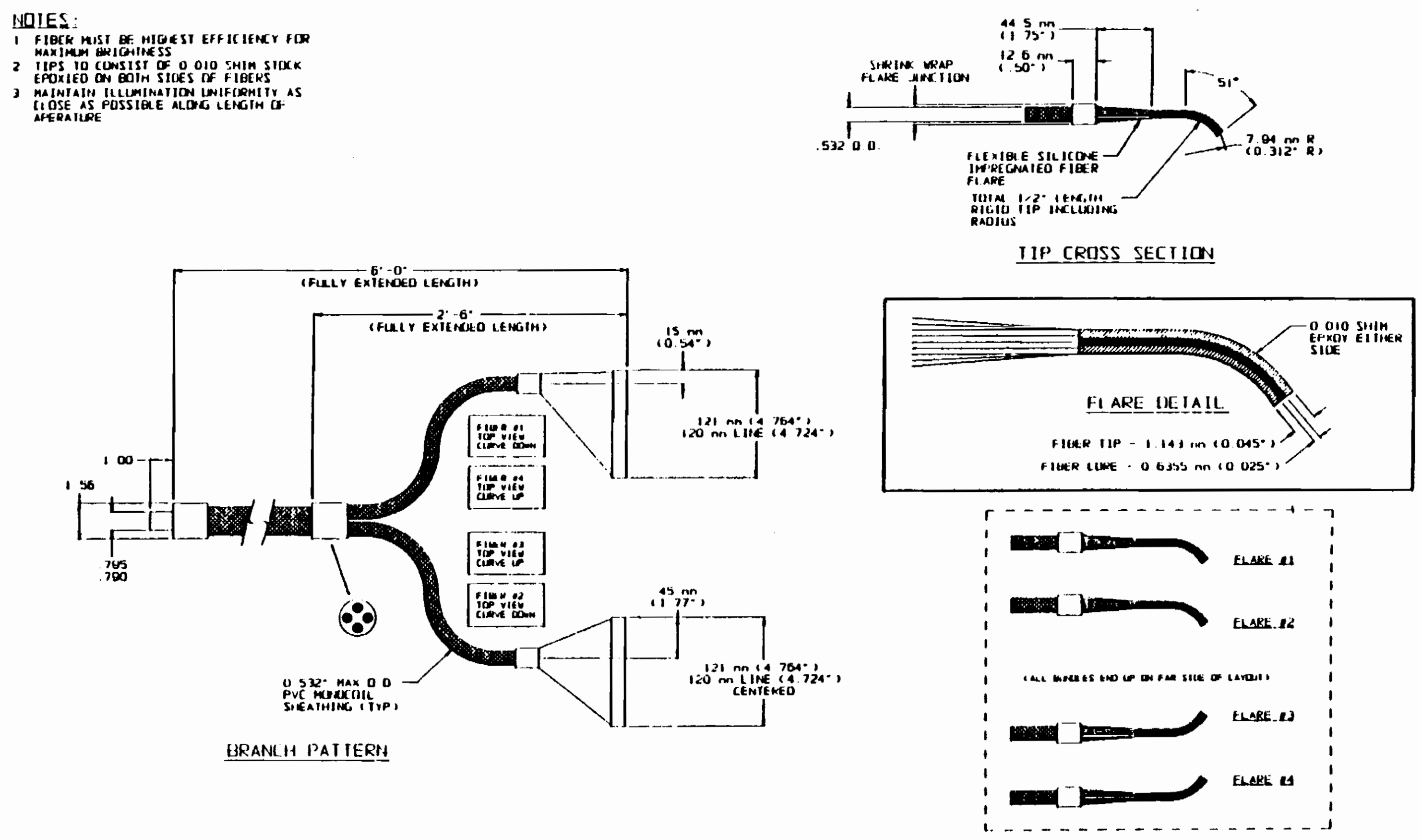


Figure A.6: Fiber-optic Design

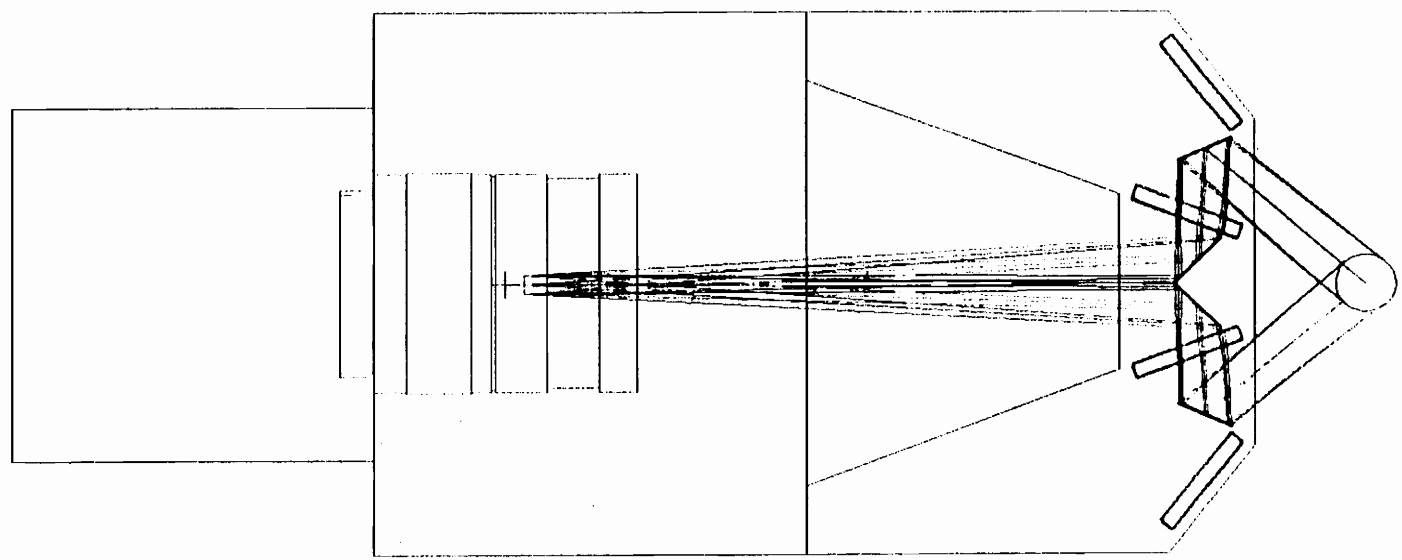


Figure A.8: Optical Imaging Path

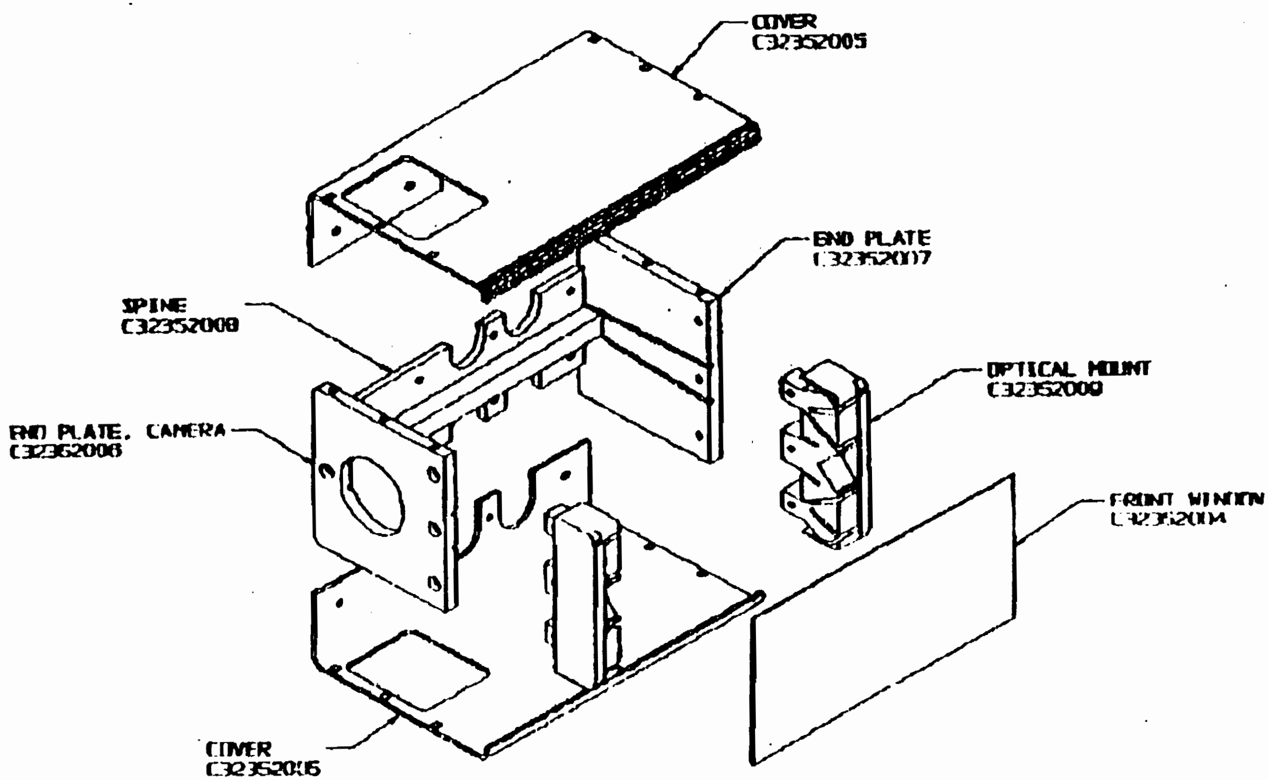


Figure A.7: Optical Assembly Enclosure

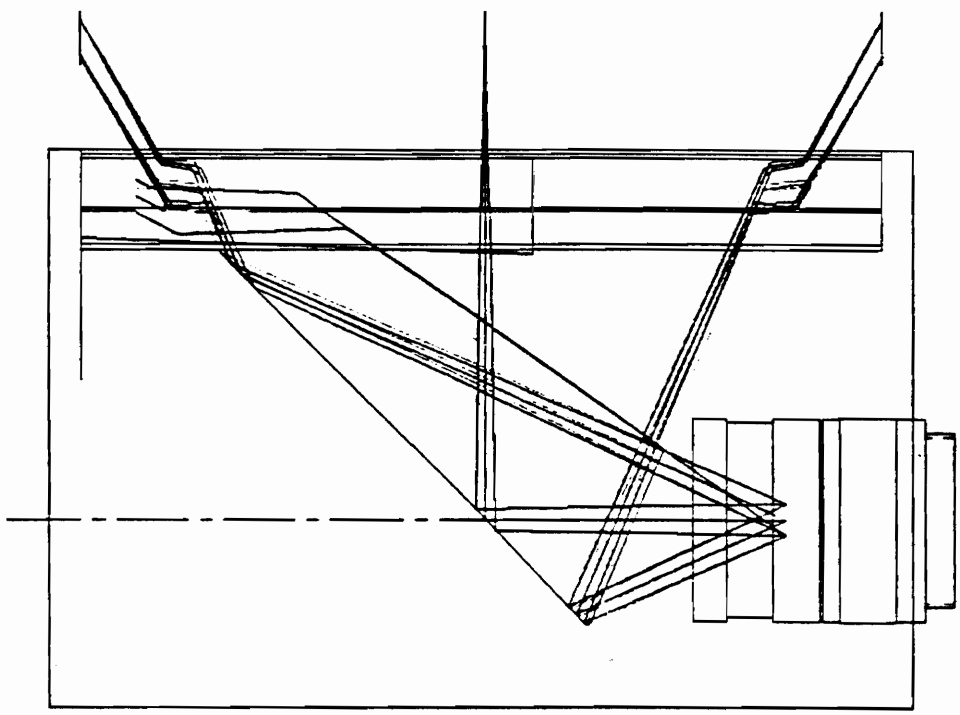


Figure A.9: 90 Degree Optical Imaging Path

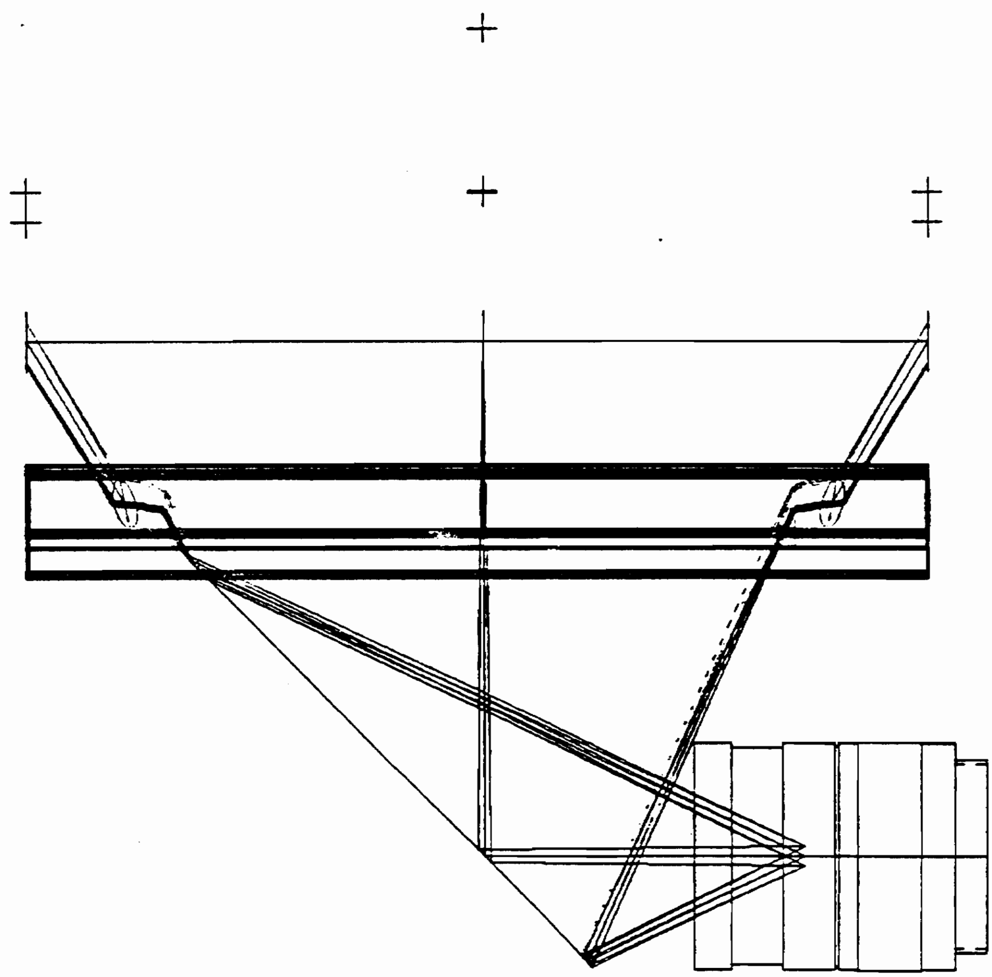


Figure A.10: 90 Degree Maximum Optical Path with Focal Points

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Vita

Barry S. Smith was born May 19, 1958, in Hopewell, Virginia. He Graduated from Prince George High School, Prince George County, Virginia, 1976. He attended John Tyler Community College where he earned a Associate of Science degree in Electronic Engineering Technology in May, 1986. He also earned a Bachelor of Science degree in Electronic Engineering from Virginia State University in May, 1988.

Barry continued his education will working as a journeyman electrician for Philip Morris, U.S.A. After graduation, Barry began a career with Philip Morris Engineering as an electrical engineer.

Barry is now with Philip Morris Research and Development in Richmond, Virginia. In his current position as a research engineer in the Physical Research Division, he is involved with technology development.

He began graduate studies in Systems Engineering at Virginia Polytechnic Institute and State University in September, 1989.

Barry S. Smith

Barry S. Smith
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April 18, 1993