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# An obstruction detection system for a coal furnace.

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# AN OBSTRUCTION DETECTION SYSTEM
# FOR A COAL FURNACE

by

Michael A. Wu

A Thesis
Presented to the Graduate Committee
of Lehigh University
in Candidacy for the Degree of
Master of Science in
Electrical Engineering

## Certificate of Approval

This thesis is accepted and approved in partial fulfillment of the requirements for the degree of Master of Science.

5/14/82

Date

Professor in Charge

Chairman of Department

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# ABSTRACT

This thesis deals with the detection of obstructions due to slagging in the ash hopper of a coal furnace. The source of the problem and possible solutions are discussed. It is decided that the system should use a laser to optically detect the presence of an obstruction.

The overall design and design problems of the system are discussed. The transmittance of the furnace atmosphere is calculated to be about 60%. Considerations in choosing a laser are discussed, with the conclusion that a 5mW HeNe laser is adequate for the system.

The necessary components for a test system are described. These include an aiming system for the laser and a receiving system to detect the beam at the other end of the furnace. The attributes of various detectors are discussed; a photomultiplier is used in the receiver design. The aiming system is designed for manual control but can easily be adapted to automatic control.

Finally, an automatic control system is proposed. The required functions for the control system are defined. The necessary adaptations to the existing components to form a reliable, automatic system are also described.

# CHAPTER 1

## DESCRIPTION OF FURNACE AND STATEMENT OF PROBLEM

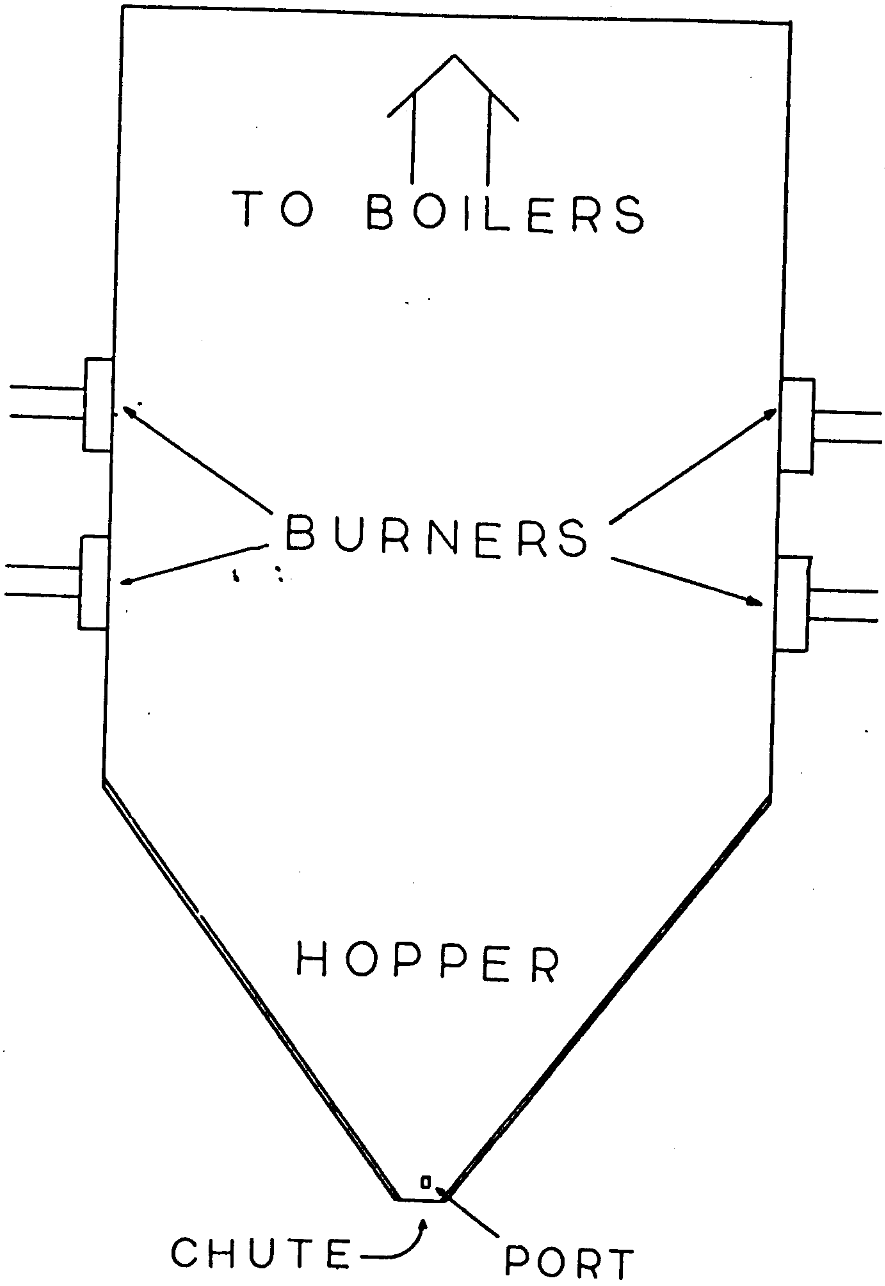
This thesis deals with the detection of blockages in the ash hopper of a coal-burning power plant furnace. Minor obstructions can become serious if not removed within a short period of time; eventually the furnace will have to be shut down to remove the blockage. This can be very costly in terms of both labor and lost time on line.

The furnace, for which the system is designed, is located at PP&L's Montour power plant in Washingtonville, Pennsylvania. It is a pulverized coal burning unit with water-cooled furnace walls and dry ash removal. A simplified cross-section of the furnace is shown in figure 1-1.

A mixture of pulverized coal and air is blown into the interior of the furnace where it is burned. The mixture is blown in such a fashion that it forms a vortex in the middle of the furnace. The furnace is divided in half across its width, so that two sets of blowers form two seperate vortices. When the furnace is fired up, an amount of fuel oil is mixed with the coal dust to ease ignition; however, once started combustion is self-sustaining.

As the coal burns it produces heat which rises up out of the furnace to the boiler, where it passes through heaters and superheaters which convert water into superheated, high-pressure steam. This steam is taken away to the turbines which turn the generators to produce electricity. The turbines and generators are located in a building away from the furnaces.

**Figure 1-1: Furnace Cross-Section**



Water cooling the furnace walls serves two purposes. First, it controls the temperature of the gases leaving the furnace for the boiler. Secondly, it encourages larger particles of coal ash to precipitate in the furnace rather than pass into the boiler and foul the heater pipes. About 20% of the ash is removed in this manner [1]. The remaining 80% is sufficiently fine to pass through the boilers without fouling to be removed by electrostatic precipitators before reaching the atmosphere. It is the 20% remaining in the furnace which is the root of the problem.

The water-cooled walls encourage larger pieces of ash to precipitate on them. This process is called slagging, and the residue on the walls is called slag. Ideally the slag should not adhere to the walls but instead should solidify and fall down to the hopper section in the bottom of the furnace. From there it passes through a chute out the bottom of the furnace into a water-filled cooling pit.

The problem occurs when the slag sticks to the walls; this happens if the walls are too cool. Once it starts sticking to the walls, more slag sticks to it and soon there is a thick layer of coal ash on the walls. When the layer gets too thick, large pieces break off and fall into the hopper. If the piece is too big it will get stuck in the chute in the bottom of the hopper. The blockage will grow larger as more ash sticks to it, until the furnace has to be shut down in order to remove it.

There is a solution to this problem. If a blockage in the chute is detected early enough, it can be manually lanced (melted with high-pressure steam). To be successfully lanced, the blockage must be detected while still semi-molten. Due to the high intensity of the light (from the furnace) in the chute there is limited visibility, so a blockage would remain invisible to the naked eye. The purpose of this project is to design a system to detect a blockage before it becomes too hardened to lance.

There are several limitations on the system design. The most significant is the access available at either end of the furnace. The available openings are only five by ten centimeters, so the system must not require large-scale access to the furnace interior. Also, these ports are opened when lancing is done; therefore, the system should be easily removed from the wall.

Another problem is the hostile environment within the furnace. System components must be protected from or be immune to the heat within the furnace. If the system requires direct access to the furnace, aspirating air can be blown into the port to prevent hot air from leaving the interior.

A third problem is the atmosphere within the furnace. The system must be able to differentiate between a cloud of ash particles or steam from the cooling pit and a blockage.

Finally, the port openings are not necessarily directly in line with each other due to the expansion of the furnace during firing-up. While the mismatch of the ports may be only an inch or two, a highly directive system may require constant re-aiming.

# CHAPTER 2

# APPROACHES TO THE SOLUTION

The basic idea of the system is to inject a signal into one end of the furnace and receive it at the other end. By comparing the received signal to the transmitted signal, the existence of a blockage can be determined. The criterion for the decision could be either signal attenuation or propogation time, depending on the nature of the signal.

Three types of signals were considered: ultrasonic (acoustic), microwave (radar), and laser (light). Although the first two types can also be used to find the distance to a blockage rather than just the existence of a blockage, they both have significant drawbacks which make them very difficult to implement.

## 2.1 Acoustic Ranging

The first method of detection considered was acoustic ranging. The idea is to introduce a short acoustic pulse into the furnace and receive its echo (essentially an acoustic "radar"). The time needed to receive an echo would be shorter if a blockage existed than if one did not exist. The distance to the blockage can be computed from the echo time. Figure 2-1 illustrates this method. Two systems would be required, one for each side of the furnace.

The main problem with this method is obtaining a transducer which can produce enough acoustic energy at the desired frequency of operation. To obtain a reasonable amount of directivity, the signal would have to be in the ultrasonic range, ideally above 50

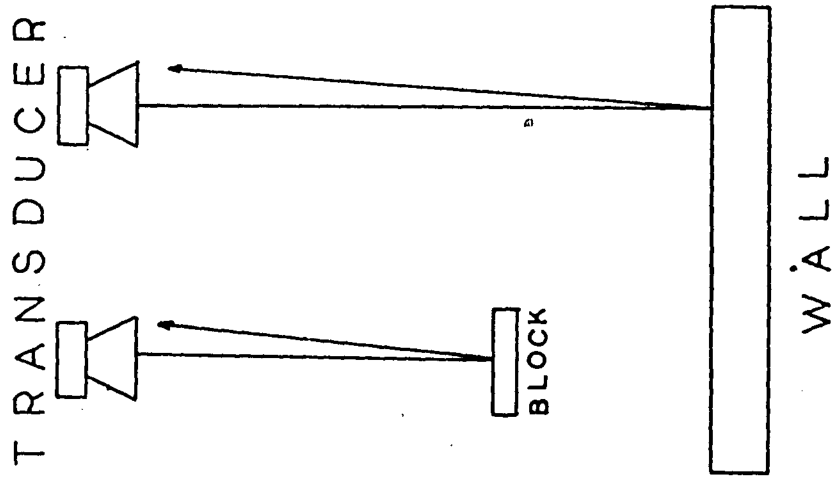
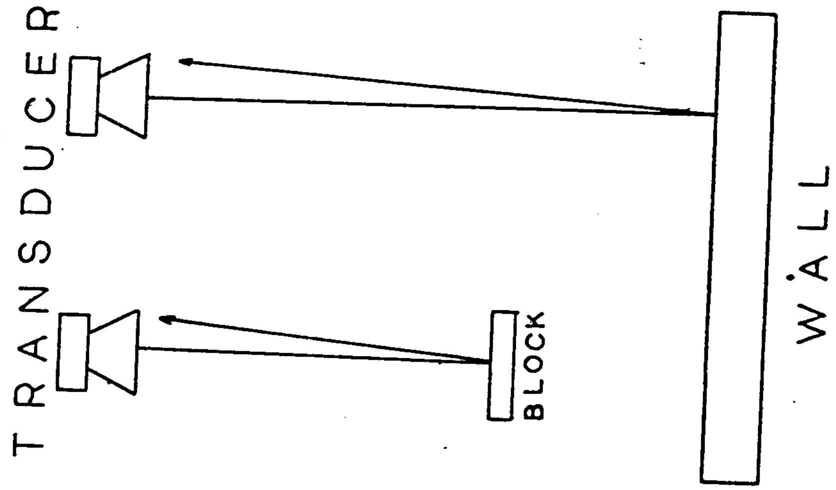


Figure 2-1: Acoustic Ranging Method

khz. Obtaining a receiving device operating in this range is also very difficult. Most transducers which are capable of producing and detecting signals at these frequencies are designed to operate in water, not air.

By moving down in frequency to about 25 kHz, transducers for both sending and receiving are much more readily available. Unfortunately, at the lower frequencies adequate directivity is not easily attainable. With insufficient directivity, detection becomes impossible because of a multitude of reflections from other parts of the furnace.

Two other serious problems exist with this method. First, temperature gradients and air movement can cause significant signal attenuation even under laboratory conditions. The more severe temperature gradients which certainly exist within the



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Two other serious problems exist with this method. First, temperature gradients and air movement can cause significant signal attenuation even under laboratory conditions. The more severe temperature gradients which certainly exist within the furnace may even cause false reflections. Second, to properly interface with the furnace requires an open air path between the transducers and the furnace interior. This makes it very difficult to protect the fragile transducers from the harsh environment within the furnace.

### 2.2 Microwave Ranging

The second method considered was a microwave ranging system. This is similar in concept to the acoustic ranging system, but using microwaves instead of acoustic waves. The immediate problem here is the size of the openings available into the furnace. Getting a high degree of directivity in reception would require a dish antenna much larger than the available opening, thus making this system impractical [2].

### 2.3 Laser Detection System

Using a laser as the signal source avoids the most serious problems of the previous systems. The aperture into the furnace required is of minimal size (less than three centimeters). Also, the laser can transmit through glass windows, thereby isolating the components of the system from the hostile environment within the furnace; this advantage is not available with the other systems.

The problem of background light is easily surmounted by optical filtering. Very sharp filters are available for most common laser lines. The main problem with this system is aiming the laser; the beam is so directive that it can easily miss the small aperture at the opposite end of the furnace.

Although this system cannot range the blockage, it will be able to fulfill the basic requirement of the project; that is, it will be able to detect a blockage in the furnace when it occurs.

# CHAPTER 3

## OVERVIEW OF SYSTEM

The block diagram of the system is shown in figure 3-1. The system is divided into three main parts:

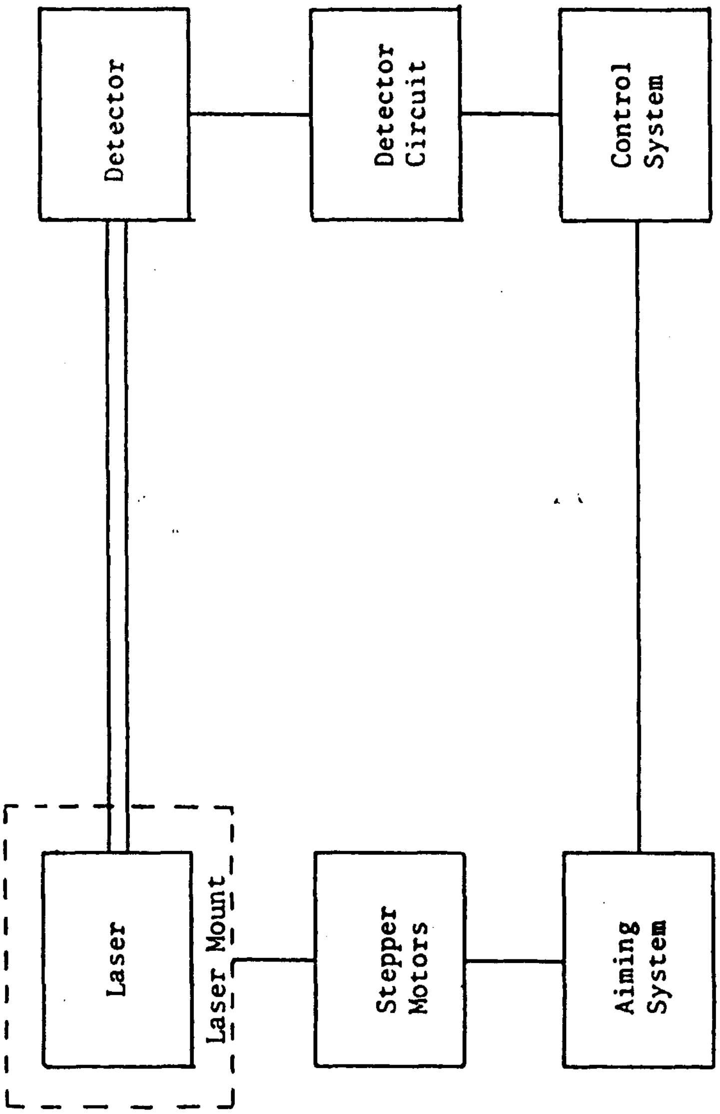
1. optical path
2. mounting and aiming system
3. control and analysis system

The optical path consists of the laser, the receiver, and associated components. The laser is the signal source for the system. It is characterized by its output wavelength and its output power. The receiver is an electro-optical device which converts incoming photons into a current or a voltage. The associated components are the optical windows, which isolate the system from the furnace, and the optical filter, which attenuates the light reaching the detector except at the laser frequency. The filter used has a peak transmittance of 30% and a 0.5 nm half-power bandwidth (equivalent to an electrical filter with a Q of over 1200).

The mounting and aiming system provides both a stable mount for the laser and the means to scan the laser beam over the far wall of the furnace for the purpose of aiming. This scanning is done by a standard optical translation device driven by stepper motors.

The control and analysis system has three functions: to automatically power the system up and down, to run the aiming

Figure 3-1: Block Diagram



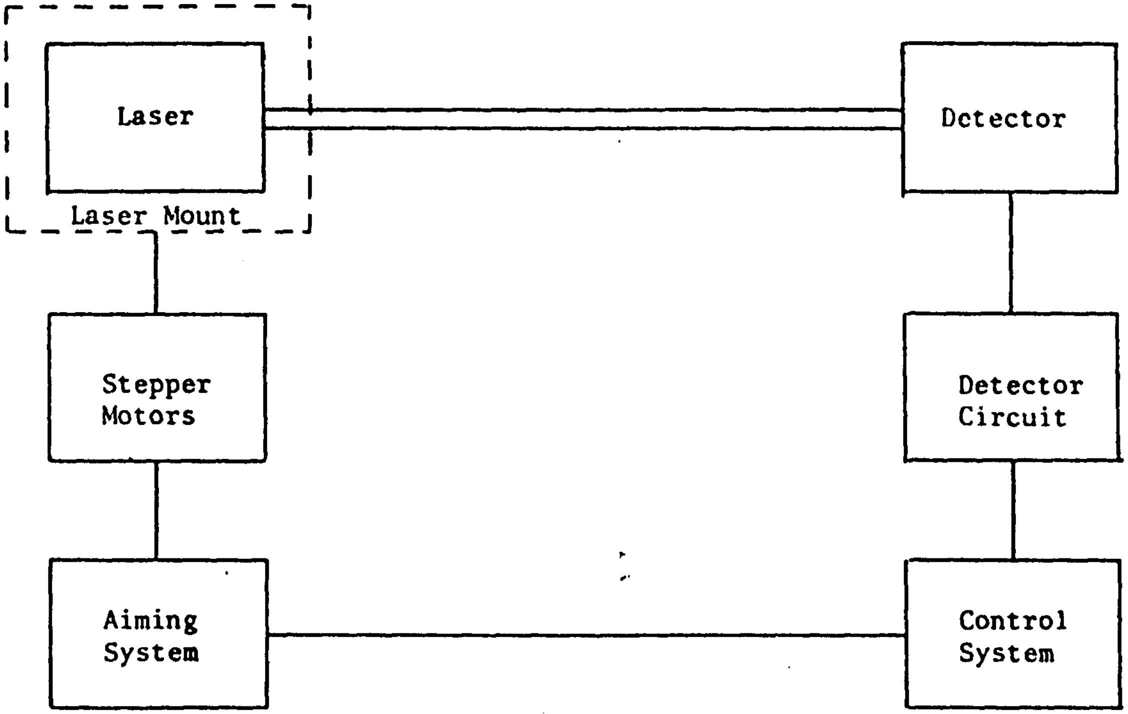


Figure 3-1: Block Diagram

system, and to analyze the received signal to determine the existence of a blockage. These functions could be most easily accomplished by a microprocessor based control system.

# CHAPTER 4

# CHOICE OF LASER

There are four factors to be considered when choosing the laser for the system. These are wavelength, power, size, and cost. The wavelength can affect the amount of light transmitted through the furnace. The wavelength must not be too short or absorbtion by water vapor becomes a problem. If the wavelength is too long, scattering becomes more significant. It turns out that the helium-neon laser at 632.8 nm is adequate to fulfill the above considerations. Also, lasers of this type are common and inexpensive.

The power required from the laser depends on the transmittance of the optical path. The transmittance is determined by the windows into the furnace, the filter at the receiver, and the atmosphere within the furnace itself. Manufacturers' specifications give the window transmittance at about 85% each and the peak filter transmittance at 30%. The transmittance of the atmosphere in the furnace is determined in the following chapter. The total transmittance of the path is given by the product of the transmittances of the various factors in the path. The transmittance of the optical components alone (ignoring atmospheric effects within the furnace) is about 22%.

Size and cost of the laser system depend on wavelength and power. A helium-neon laser delivering 5 mW will easily fulfill the size and cost requirements. Lasers delivering this power are available from a large number of companies. An increase in power to 7 mW (the next higher readily available power) would not be worth the extra cost; as will be shown later, 5 mW is quite enough power for effective transmission.

# CHAPTER 5

# TRANSMISSION OF THE OPTICAL PATH

There are two phenomena which cause signal attenuation in the atmosphere within the furnace. These are particle scattering and molecular absorbtion and scattering. Particle scattering is discussed in the first section; molecular absorbtion and scattering are covered in the second.

## 5.1 Particle Scattering

Light incident on a particle is scattered in one of two ways, depending on the size of the particle relative to the wavelength of the incident light [3]. If the particle is smaller than about one-tenth the wavelength, Rayleigh scattering takes place; equal amounts of light energy are scattered forward and backward. This type of scattering is typical of gas molecules. The other type of scattering occurs when the particle is larger than one-tenth the wavelength; this is called Mie scattering. In Mie scattering, a significantly greater amount of light energy is scattered forward than backward; the larger the particle, the higher percentage of incident light is scattered forward.

The separation between particles is also significant. If the particles are separated by several radii, no coherent phase relationships exist between the scattered waves and the process is called independent scattering. The intensity of the light rather than the amplitude of the waves is additive. The particles in the furnace act as independent scatterers. The corresponding process for closely spaced particles is called diffraction.

The primary source of particles within the furnace is ash. When the coal burns, about 15% of it becomes ash [1]. The ash particle is generally about one-fifth the size of the coal particle which produced it [4]. Since 80% of the ash rises out of the furnace, only the heaviest 20% of the particles falls into the optical path. It is assumed that these are produced by the heaviest 20% of the coal particles.

The size distribution of the pulverized coal can be derived from the Rosin and Rammler equation [5]:

$$R = e^{-(x/x_o)^n}$$

where R is the fraction by weight of the coal sample remaining in a sieve with openings x across, and where $x_o$ and n are constants. The amount passing through a sieve with openings x across (the amount with diameter less than x) is given by:

$$P = 1-R = 1-e^{-(x/x_o)^n}$$

This represents the area under the distribution curve for the weight of coal of a particular size. This distribution function can be determined by taking the derivative with respect to size of the above equation:

$$F(x) = dP/dx = n(x/x_o)^{n-1}e^{-(x/x_o)^n}$$

This gives the fraction of the total coal which has a diameter x. The weight of coal of diameter x burned per second is:

$$W_c(x) = W_{tc}F(x) = W_{tc}n(x/x_o)^{n-1}e^{-(x/x_o)^n}$$

where $W_{tc}$ is the total weight of the coal burned per second.

To find the distribution of ash particles vs. ash particle diameter, $\dot{W}_a(y)$, the following substitutions must be made:

$$\dot{W}_a(x) = 0.15\dot{W}_c(x), \quad x = 10y$$

where y is the radius of the resulting ash particles. This gives

$$W_a(y) = 1.5W_{tc}n(10y/x_o)^{n-1}e^{-(10y/x_o)^n}$$

which is the weight of ash particles of radius y generated per second. The factors 0.15 and 10 are due to the size difference between an ash particle and the coal particle which produced it.

The weight of a single particle of radius y is given by

$$w = SV = 1.33\,\pi y^3 S$$

where S is the specific gravity of the ash. The specific gravity of the ash can be determined from the specific gravities of its four major constituents by

$$S = [\Sigma\, w_n/S_n]^{-1}$$

where $w_n$ is the fraction by weight of constituent n and $S_n$ is the specific gravity of constituent n. The constituents of a typical ash sample from eastern coal are [4]:

| | | |
|---|---|---|
| $SiO_2$ | 48.0% | S = 2.3 |
| CaO | 17.1% | S = 2.3 |
| FeO | 13.5% | S = 5.7 |
| $Al_2O_3$ | 12.5% | S = 4.0 |

Using this data the above equation gives S=3.17 (use S=3 since the actual value will vary widely depending on the type of coal used.) Thus

$$w = (4\,\pi \text{gm/cm}^3)y^3$$

is the weight of a single ash particle of radius y.

We can now express the distribution of the number of ash particles of radius y by

$$N_p(y) = \frac{W_a(y)}{W} = 0.325\ \frac{W_{tc}}{\pi y^3} n(10y/x_o)^{n-1} e^{-(10y/x_o)^n}$$

where $N_p$ is the number of particles of radius y generated per second. If we assume that the particles are evenly distributed throughout the furnace, and the horizontal area of the furnace is $A_h$, the number of ash particles produced per unit area of the furnace per second is

$$N_h(y) = \frac{N_p(y)}{A_h}$$

Given this number and the speed with which the particles fall, the concentration of particles in the optical path becomes

$$N(y) = \frac{N_h(y)}{U(y)} = \frac{N_p(y)}{A_h U(y)}$$

where U(y) is the terminal velocity of a particle of radius y.

If the assumption is made that the air in the lower part of the furnace is motionless (not strictly accurate but good enough for an approximate analysis), the terminal velocity can be found from Stokes' equation for spheres moving in a fluid [6]:

$$U = \frac{2y^2(w_s - w_m)}{9u}$$

where u is the viscocity of the fluid, $w_s$ is the specific weight of the sphere, and $w_m$ is the specific weight of the fluid. In the case of a particle falling through the air, $w_s >> w_m$ and the equation reduces to

$$U = \frac{2y^2 Sg}{9u}$$

where g is the gravitational constant. Solving the above equations for N(y) gives

$$N(y) = \frac{9uW_{tc}n}{2A_h Sg\pi} \; 0.325 \; \frac{cm^3}{gm} \; y^{-5}(10y/x_o)^{n-1} e^{-(10y/x_o)^n}$$

The following are typical values for the above parameters [1, 5, 7]:

$$u = 182 \text{ upoises}$$
$$A_h = 3 \times 10^6 \text{ cm}^2$$
$$W_{tc} = 3000 \text{ tons/day} = 1.53 \times 10^5 \text{ gm/s}$$
$$n = 1.41$$
$$x_o = 60 \text{ um}$$

Substituting these values into the equation for N(y) gives

$$N(y) = (2\times10^{-8}\text{cm}^2) y^{-5} (1670y)^{0.41} e^{-(1670y)^{1.41}}$$

The transmittance for the optical path is given by [3]

$$\%T = 100e^{-\beta z}$$

where z is the total path length and $\beta$ is the total attenuation coefficient, which is the sum of coefficients for particle scattering, molecular scattering, and molecular absorbtion. The coefficient of particle scattering is given by [3]:

$$\beta_{sc} = \int N(y)\ y^2 Q_{sc} dy$$

integrated over the range of particle radii present. $Q_{sc}$ is the efficiency of scattering, which approaches 2 for particles much larger than the wavelength of the incident light.

We can determine the scattering coefficient for the typical case by taking the integral in the above expression over the appropriate limits. Typically the heaviest 20% of the coal particles are larger than 80 um [1]; integrating from y=8.0 um to infinity numerically gives a scattering coefficient of 1.49 x $10^{-3}$ $cm^{-1}$. If scattering alone is considered, this gives a transmittance of about 2.73%.

### 5.2 Molecular Absorbtion and Scattering

As was mentioned before, the scattering process involving molecules is Rayleigh scattering. When the particle size is small compared to the wavelength of the incident light, Rayleigh scattering occurs. Equal amounts of flux are scattered forwards and backwards. Atmospheric molecules certainly are small enough to be considered Rayleigh scatterers for the wavelength of light used. However, over short distances the effects of Rayleigh scattering are negligible; the scattering cross-section is small due to the low molecular density of the atmosphere.

The other effect which causes attenuation of the laser beam is molecular absorbtion. Constituent atmosphere molecules absorb photons of various wavelengths depending on their chemical compositions. Thus the attenuation due to absorbtion is dependent both on the frequency of the incident radiation and the quantity of the absorber.

Assuming that the gases of combustion all rise out of the furnace, the atmosphere within the channel is close to normal composition and pressure. The exception is the existence of large amounts of water vapor from the cooling pit below the furnace. Experimental data is available for the transmittance of the atmosphere for various amounts of water vapor [8]. The amount of water in an optical path is given in centimeters of precipitable water (the depth of water which would precipitate out of the optical path if it were stood on end). If we assume a worst-case water vapor concentration of about $3.1 \times 10^{-4}$ gm/cm$^3$ (the saturation concentration of water vapor at 374°C [9]) there would be 0.80 centimeters of precipitable water in the path. From the experimental data, this gives a transmittance of about 90%.

## 5.3 Total Transmittance

The total transmission coefficient for the optical path is the sum of the transmission coefficients for the various effects [3]. Solving the transmission equation for the transmission coefficient gives a coefficient of $4.13 \times 10^{-5}$ $cm^{-1}$ for the molecular effects. Summing the transmission coefficients and solving the transmission equation gives a total transmittance of about 2.65% for the optical path within the furnace. Including the effects of optical components gives a total transmittance of 0.6%.

# CHAPTER 6

# DETECTION SYSTEM

## 6.1 Detectors

Optical detectors fall into two general categories: thermal detectors and photon detectors [10]. Thermal detectors operate by sensing a change in temperature on the detector surface due to the incident radiation. They are generally used to detect radiation in the middle and far infrared and are very inefficient at visible wavelengths. Photon detectors utilize the fact that an atom can absorb a photon and emit an electron if the photon is of sufficient energy. The effect of excess electrons is easily detected. These detectors generally operate at near infrared and shorter wavelengths.

There are three types of photon detectors which may have an application here. They are photoemissive detectors, photoconductive detectors, and photovoltaic detectors. There are several other more esoteric detector types available, none of which would be practical in this system.

Photoemissive detectors rely on the photoelectric effect. A photon of sufficient energy striking a photoemissive surface causes an electron to be ejected from the surface. The energy of the ejected electron is given by

$$E = hf - q\phi$$

where h is Planck's constant, f is the frequency of the incident radiation, q is the electronic charge, and $\phi$ is the work function of the material. For an electron to be emitted, the energy hf of the photon must be greater than the $q\phi$ of the material. This implies that the frequency of detected light must be above a particular threshold in order to be detected by a particular photoemissive material.

The most useful photoemissive device is the photomultiplier. This device relies on secondary emission (in addition to the primary photoemission) in which an electron striking a surface transmits its kinetic energy to the atoms in the surface. If the kinetic energy of the incident electron is sufficient, several electrons can be knocked out of the surface. This process is repeated several times in a photomultiplier. A simplified schematic of a photomultiplier is shown in figure 6-1.

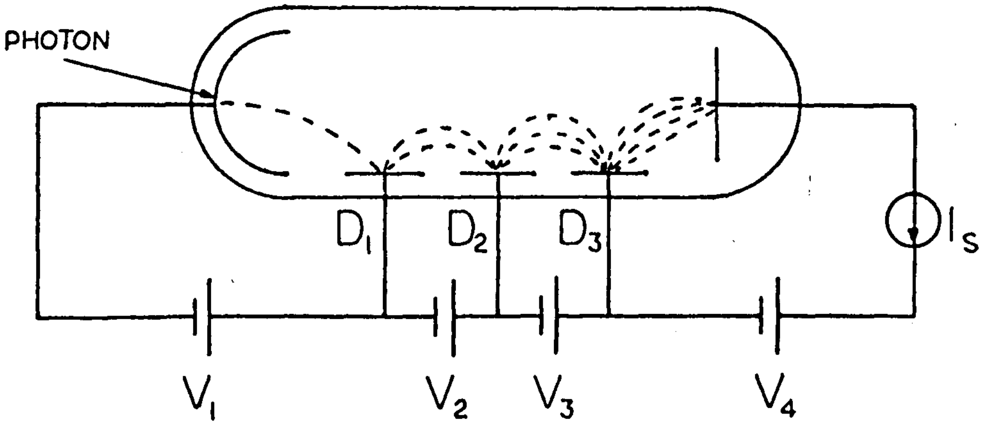


**Figure 6-1:** Photomultiplier Schematic

The light incident on the cathode causes an electron to be emitted. This electron is accelerated by the electric field caused by $V_1$ and focused on dynode $D_1$. The secondary electrons emitted from $D_1$ are then accelerated by $V_2$ and focused on $D_2$. This process continues until the electrons are collected by the anode. Thus a single incident photon can cause the collection of many electrons at the anode, making the photomultiplier a highly sensitive device.

Photoconductive detectors rely on the excitation of ground-state electrons to higher energy states where they can participate in electrical conduction. This can be explained in terms of the band theory: if a valence band electron absorbs a photon of sufficient energy, it can be excited to jump the energy gap to the conduction band. This creates a free electron-hole pair, increasing the number of free carriers. Since the conductivity of the material is directly proportional to the concentration of free carriers, the resistance of the material decreases. Photoconductive materials are generally semiconductors, since they have energy gaps which can be overcome by photons in the visible range. Extrinsic (doped) semiconductors can be used to decrease the amount of energy needed to free an electron (or hole, depending on conductivity type) for conduction by adding energy levels within the forbidden band. The threshold frequency for the formation of an electron-hole pair is

$$f = E_g/h \text{ or } f = E_n/h$$

depending on whether the material is intrinsic or extrinsic and where $E_g$ is the forbidden gap energy and $E_n$ is the energy difference between the impurity level and the conduction or valence band (depending on conductivity type).

The third type of detector is the photovoltaic detector. This detector relies on the generation of electron-hole pairs within a p-n junction. The electron is attracted to the n-side of the junction and the hole to the p-side due to the built-in electric field (see figure 6-2).

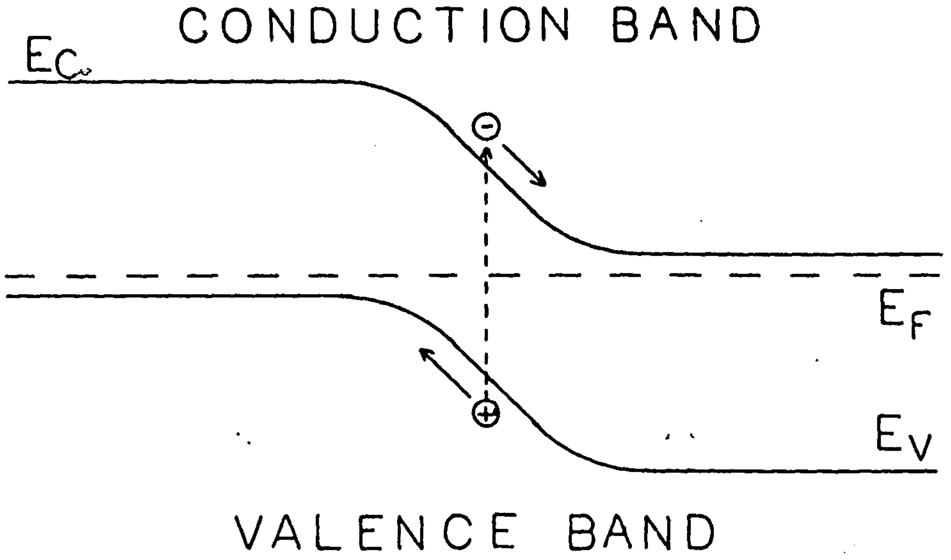


Figure 6-2: Excess Carrier Behavior in a P-N Junction

This greatly increases the reverse current if the junction is used as a diode. The variation in reverse current can be used to indicate the presence of incident radiation. Signal gain can be achieved by using the p-n junction in a transistor; the resulting device is called a phototransistor.

### 6.2 Choice of Detector

The primary consideration in the choice of detector for this system is the detector sensitivity. Using a 5 mW laser and the transmission characteristics previously calculated, about 30 uw of laser power should reach the receiver. It is imperative that the detector be sensitive enough to detect this signal with enough headroom to separate it from the background light.

At the given wavelength, a photomultiplier output is about 200 amps per watt of incident radiation. A photodiode produces only about 200 milliamps per watt. The output current for the two cases are 6 mA and 6 uA respectively. Clearly the output of the photomultiplier is more easily detected.

The device chosen is a nine-stage side window photomultiplier mounted in a magnetically shielded housing (Oriel Corp. #7060). It has a sensitivity of about 180 A/W at the laser wavelength. It is equipped with a filter holder and an input hood to prevent the input of ambient light to the detector surface.

### 6.3 Filter

The filter used is an interference type with a peak transmittance of 30% at the laser frequency (632.8 nm) and a half-power bandwidth of 0.5 nm (Oriel #5272). This filter is specifically designed to isolate a specific laser frequency from a strong white background.

The operation of an interference filter is similar to that of a Fabry-Perot interferometer. The filter shows a resonant behavior for a specific wavelength and its harmonics (constructive interference). Wavelengths outside the filter passband tend to cancel each other out (destructive interference). The result is a filter with a very narrow passband and very low background.

## 6.4 Detector Circuits

The photomultiplier gives an output current which is independent of the load. The current-to-voltage converter shown in figure 6-3 can be used to measure the output current.

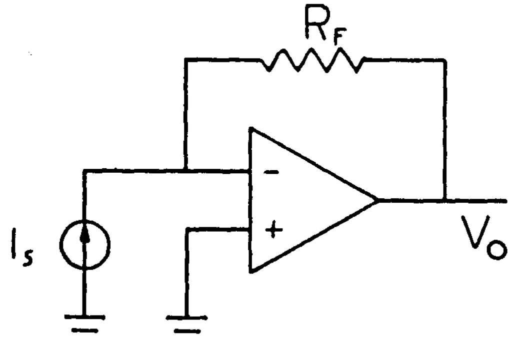


Figure 6-3: Current-to-Voltage Converter

Due to the virtual ground at the op-amp input, there is no voltage across $i_s$; this prevents any adverse loading effects on the biasing circuit. All $i_s$ flows through $R_f$, producing an output voltage $V_o = -i_s R_f$. $R_f$ is variable in order to change the sensitivity of the system (the background level can be set to a reference level).

The need to differentiate between the signal and the background can be achieved with the circuit of figure 6-4. This circuit is similar to the current-to-voltage converter but produces a go/no-go TTL output. By properly adjusting the sensitivity and the offset voltage, the output level of the background can be kept below the threshold voltage of the Schmitt trigger. When the beam is incident on the detector, the output voltage increases and the Schmitt trigger fires, sending its output low. If the current out of the photomultiplier is 6 mA due to the laser, a resistor value of 830 ohms will produce an output voltage of 5 volts.

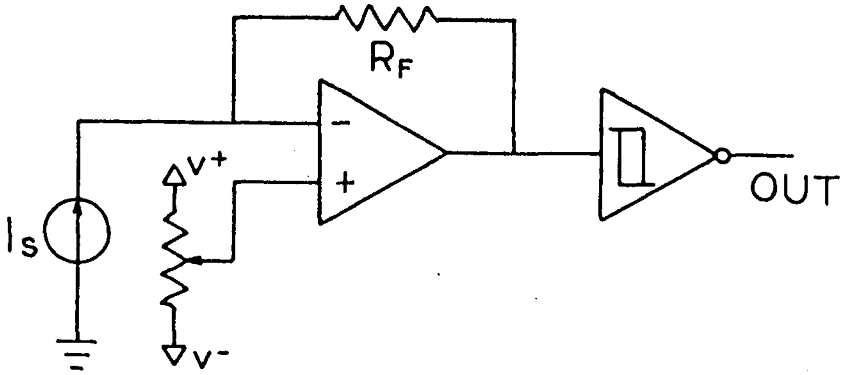


**Figure 6-4:** Improved Detection Circuit

Biasing the photomultiplier is accomplished by a voltage source and a resistive divider network between the cathode, dynodes, and anode. The divider network is internal to the photomultiplier housing, so only the supply voltage must be provided. The value of the supply voltage should be 600 V in order to maximize the photomultiplier's signal to noise ratio. A vacuum tube power supply can be used for this application.

# CHAPTER 7

# MOUNTING AND AIMING SYSTEM

The purpose of the mounting system is to provide a vibration-free platform on which the laser can be mounted. The aiming system provides the means to alter the direction of the laser beam in order to align it with the receiver at the far end of the furnace.

## 7.1 Mounting

The major difficulty in designing the mount for the laser is to eliminate the effects of vibration on the direction of the laser beam. Vibrations parallel to the direction of the beam are acceptable as long as they do not induce any angular movement of the laser. The main source of vibration is the furnace wall. Through proper design the effects of this vibration can be minimized.

The simplest possible mount is the single platform shown in figure 7-1. If it can be assumed that the displacement of the wall due to vibration is normal to its surface, as long as the mount is perpendicular to the wall the only displacement of the laser will be parallel to the optical path. However, if the mount is not perpendicular to the wall, a moment is introduced which gives an angular displacement about point x (see figure 7-2). This angular displacement is sufficient to cause serious misalignment of the beam.

The above discussion shows that to minimize the effects of

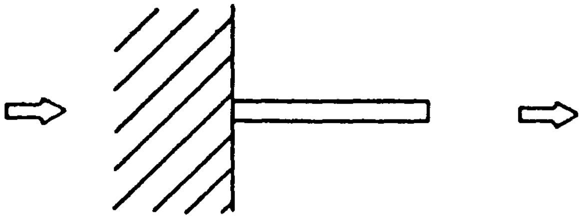


Figure 7-1: Ideal Simple Mount

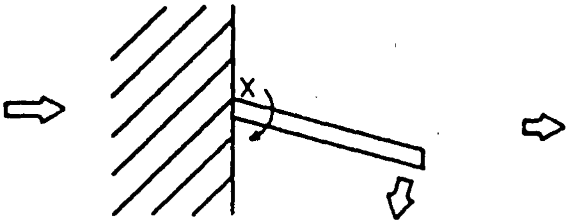


Figure 7-2: Effects of Sag on the Simple Mount

vibration, the mount must be as perpendicular to the wall as possible. This is a very difficult task with the single platform mount since the weight of the mount would make it tend to sag away from the horizontal. By making the mount a rigid frame instead of a platform, the sag problem can be eliminated. Not only would a rigid frame be less prone to sag, but any adverse effects of any sag would be minimized. To illustrate this point, see figure 7-3. Consider the moment generated around point x. This moment tries to make the frame rotate about this point. However, since the frame is also anchored at point y, it is not free to rotate. The wall exerts a force on the frame at y which provides a moment about x sufficient to cancel the moment from the vibration. Since the moment about x is now zero, there is no angular displacement.

A rigid frame is best approximated by a simple truss. A rigid

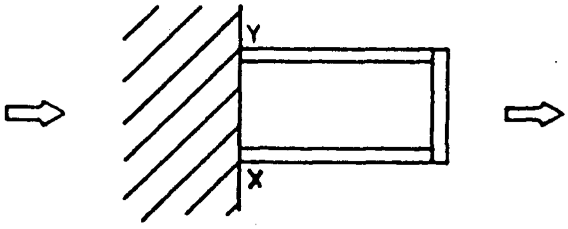


**Figure 7-3:** Rigid Mount

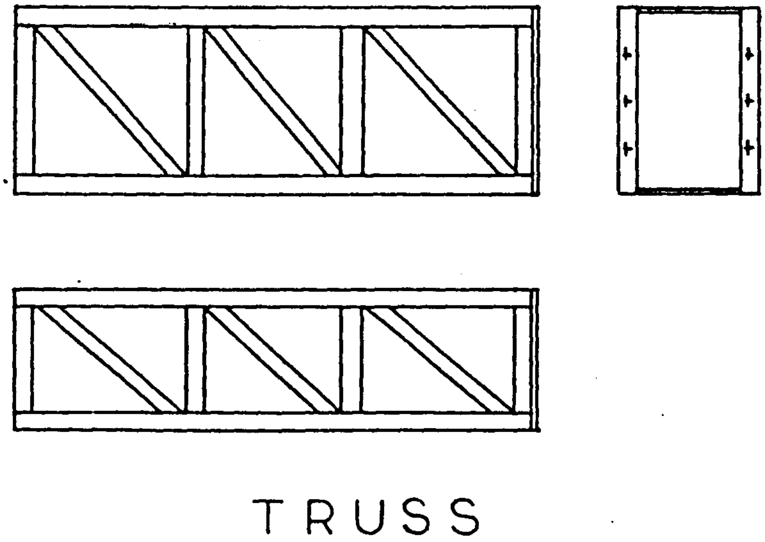
truss is one which will not deform when a force is applied to one of its joints. The frame in its final form is shown in figure 7-4. Note that there are trusses both vertically and horizontally to prevent angular displacement in either of these directions.

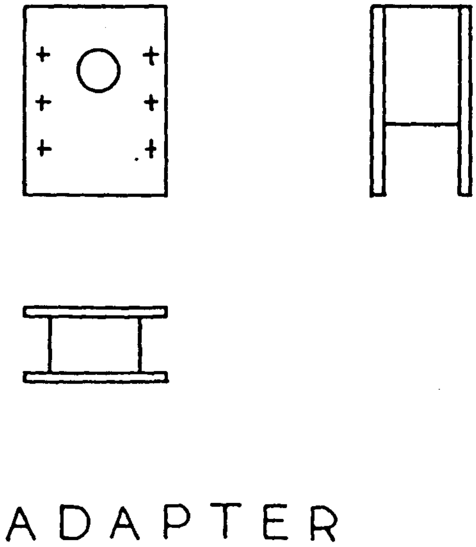
It is most desirable to mount the laser on the furnace using the bolts already there for the port doors. Therefore it is necessary to use an adapter to connect the frame to the wall. This adapter also contains the window which isolates the laser from the furnace. Since the adapter is short, sufficient rigidity can be achieved by using thick steel plate in its construction (see figure 7-4).

### 7.2 Aiming System

The aiming system consists of the laser mount and the stepper motors to drive it. The laser mount is a standard optical translation device which is capable of angular rotation about two axes perpendicular to both the optical path and each other. The rotation is controlled by two 15 turns/cm screws. These screws are in turn driven by the stepper motors. The motors are mounted away

Figure 7-4: Laser Mount - Final Version





from the frame to minimize vibration and are connected to the screws via flexible shafts.

The goal of the aiming system is to scan the laser beam across the far wall of the furnace in incremental steps and in a predetermined pattern until the beam is incident on the detector. The aiming system should require only minimum input from the controller to perform its functions.

The aiming system should hold the laser in place until it receives a triggering signal from the controller to scan the beam one incremental step. The system should then scan the beam and send a signal back to the controller when the scan is completed. Also, it should ignore any triggering signal received while scanning is in progress.

The system is divided into two parts: the stepper drive system (SDS) and the location determination system (LDS). The SDS causes the stepper motors to move the mount to scan the laser one incremental step. The LDS keeps track of where the beam is along the scan path and controls the direction in which the beam is scanning.

The stepper motors are the precision type with $1.8^{\circ}$ steps. They require the switching sequence shown in figure 7-5 to operate. Note that at all times when winding one is on, winding two is off; windings three and four behave similarly. To reverse the motor, the steps are performed in the reverse order; this is the same as switching the inputs to windings three and four. The circuit

| STEP | WNDG 1 | WNDG 2 | WNDG 3 | WNDG 4 |
|---|---|---|---|---|
| 1 | ON | OFF | ON | OFF |
| 2 | ON | OFF | OFF | ON |
| 3 | OFF | ON | OFF | ON |
| 4 | OFF | ON | ON | OFF |
| 1 | ON | OFF | ON | OFF |

**Figure 7-5:** Stepping Sequence for Motors

shown in figure 7-6 provides TTL level control signals for a stepping motor; since there are two motors, two of these circuits are required.

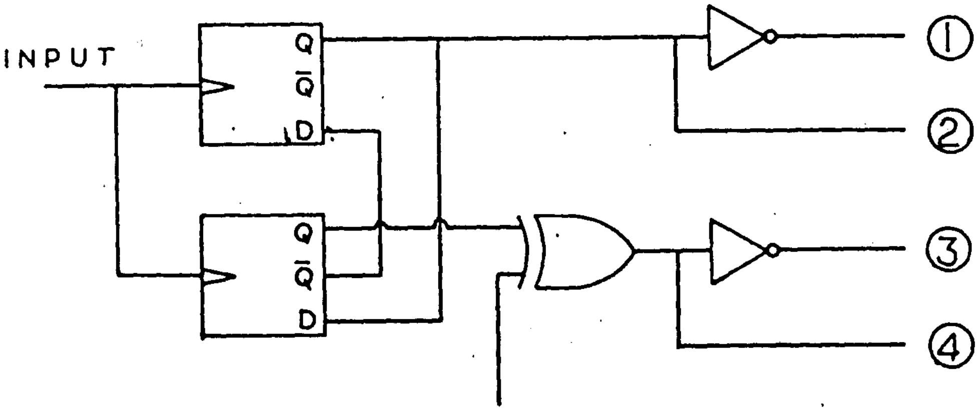


**Figure 7-6:** Step Sequence Generator

The two flip-flops produce two out of phase signals at half the clock frequency. The exclusive-or provides the capability of reversing the stepping order by inverting the signals at three and four. Note that each clock pulse causes the output to advance one step.

Each winding of the motor requires 5.8 volts at 0.85 amps. This is clearly beyond the ability of a TTL gate to deliver. The circuit in figure 7-7 acts as a buffer between the logic and the motor.

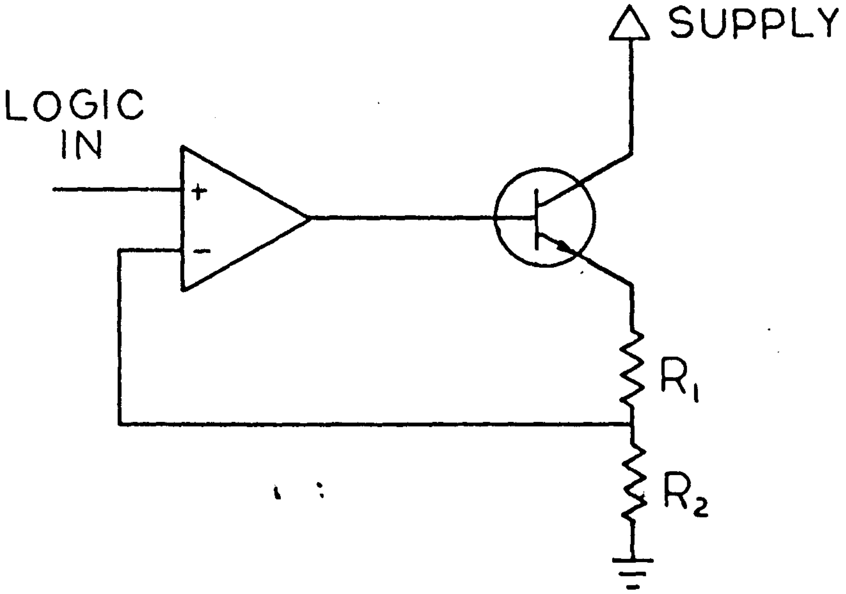


Figure 7-7: Motor Drive Circuit

This circuit is similar to a series voltage regulator, except that the reference is replaced by the logic output. Virtual ground requires that $V_{R2} = V_{in}$, so $V_o = (R_1+R_2)V_{in}/R_2$. $V_o$ can be set to 5.8 volts when $V_{in}$ is high by using a trimming resistor for $R_1$ and $R_2$. Four of these circuits are required for each motor, so a total of eight are required for the system. Care must be taken that the maximum power dissipation of the transistor is not exceeded.

So far the system can move the motors one step (1.8°) for each input pulse. Now the number of pulses required to scan the beam one increment must be determined. The screws in the positioner can move the lever arm of the positioner 0.064 cm per turn or $3.2 \times 10^{-4}$ cm per step. The distance each step moves the beam on the far wall depends on the length of the lever arm (see figure 7-8).

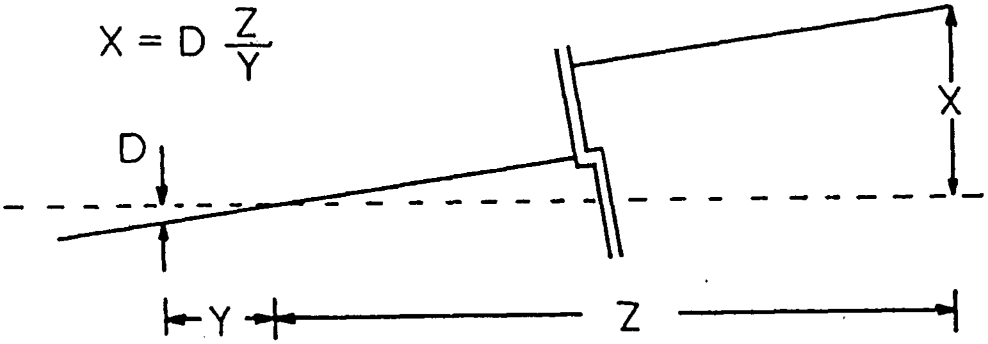


Figure 7-8: Calculation of the Scan Distance

Movement in the horizontal direction of 4.5 cm gives an x of 0.182 cm. For vertical movement of 8.5 cm, x = 0.096 cm.

Defining an incremental step as one centimeter (half the approximate size of the photomultiplier window), to move one incremental distance would require 5.49 steps horizontally and 10.4 steps vertically. Since fractional steps are not permitted, the values of 5 and 10 are used. The circuit in figure 7-9 will output a desired number of clock pulses for one input pulse. It will also deliver a signal when the count is finished. the input pulse switches the toggle, enabling the counter. When the count value is reached, the de-multiplexer output goes low, clearing the counter and switching the toggle to disable the counter. Clock pulses can flow to the stepper drive only when the counter is enabled. The clock is a free-running 555 timer operating at 50 Hz.

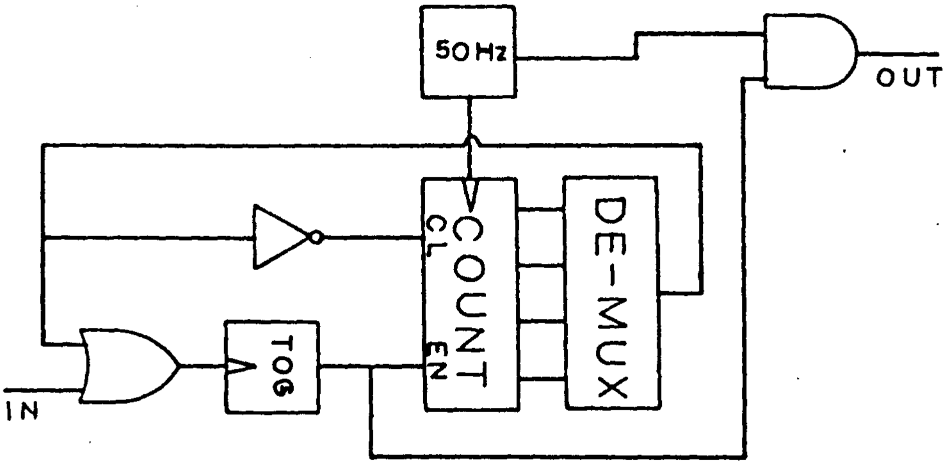


Figure 7-9: Motor Pulse Generator

The LDS consists of two sets of counters, one monitering the vertical position and one the horizontal position. The scanning pattern is a modified raster scan; the beam is swept horizontally once, then moved one increment vertically. The beam is then scanned back. Thus the direction of the scan must change when it reaches either limit. The LDS circuit is shown in figure 7-10. The input pulse increments the horizontal counter. When the counter reaches a scan limit as determined by the de-multiplexers, the direction of both the scan and count is reversed by switching a toggle. Also, when the scan limit is reached, the vertical counter is incremented. The operation of the vertical counters is similar to that of the horizontal counters.

The complete aiming system is shown in figure 7-11. In addition to the subcircuits described above, provisions are made

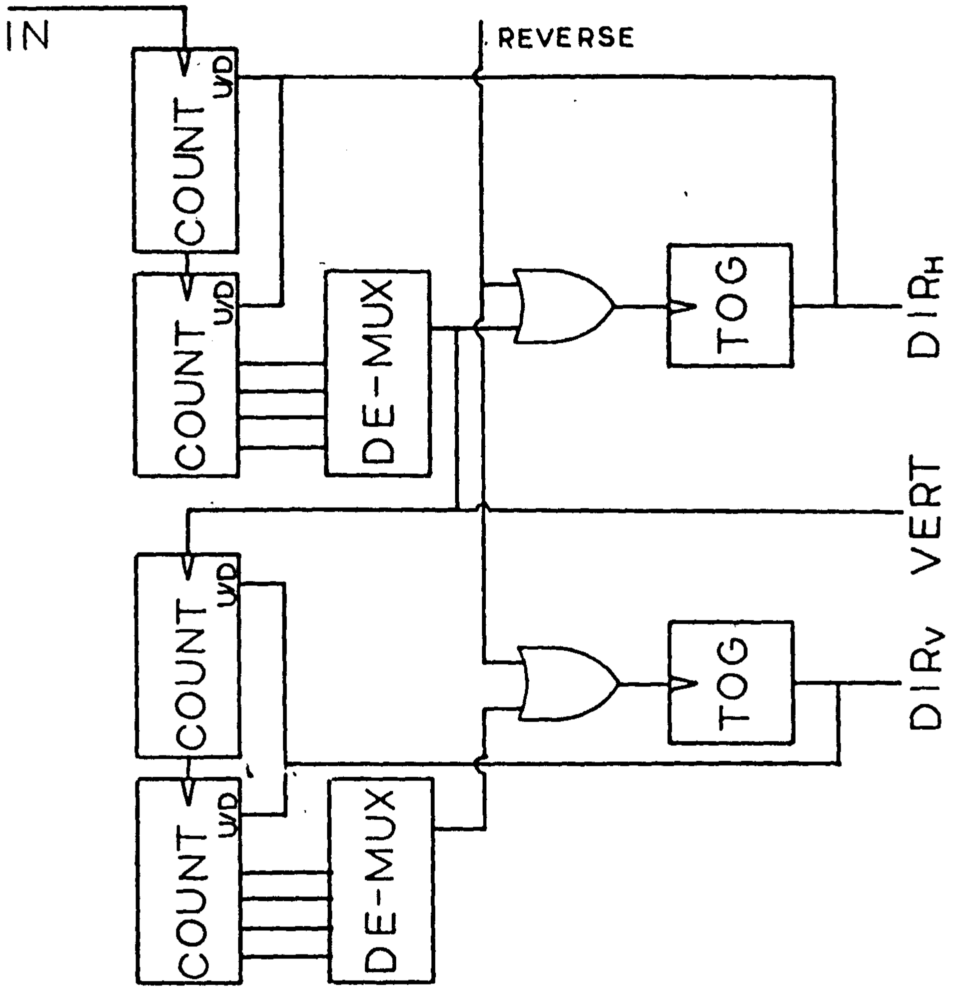


Figure 7-10: LDS System

to preset all the toggles and the LDS counters to initial values. The counters are set to a value dependent on the initial laser position by switches $S_1$ through $S_{16}$. The toggles are set so that the original scan directions are left to right and up to down and so that no pulses reach the scan drivers.

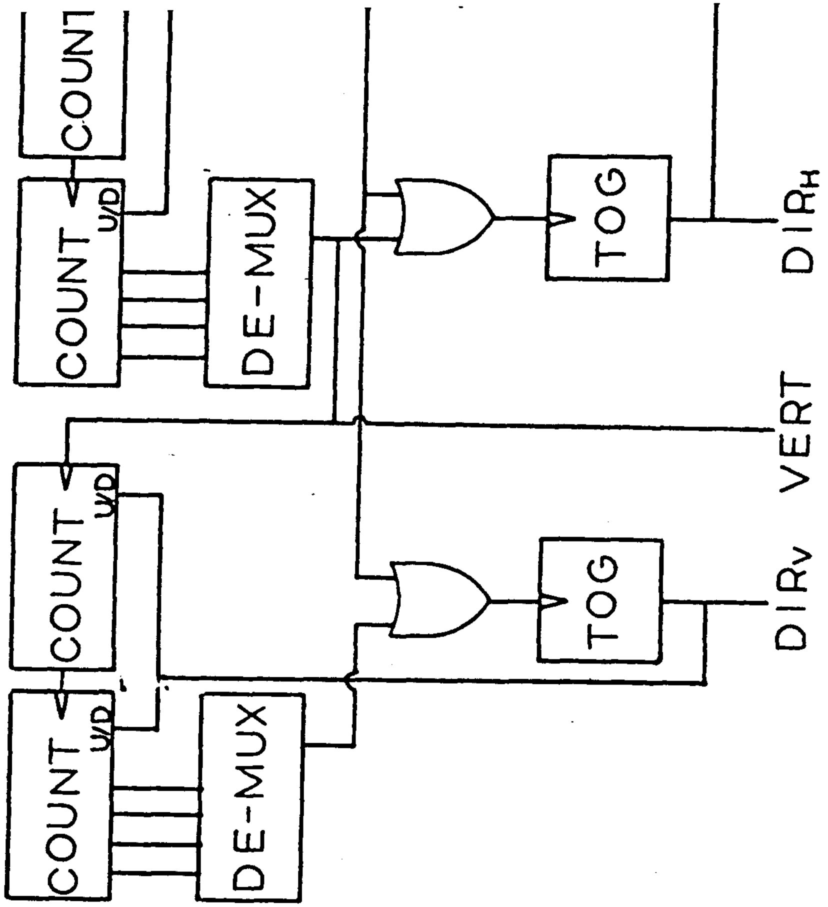


Figure 7-10: LDS System

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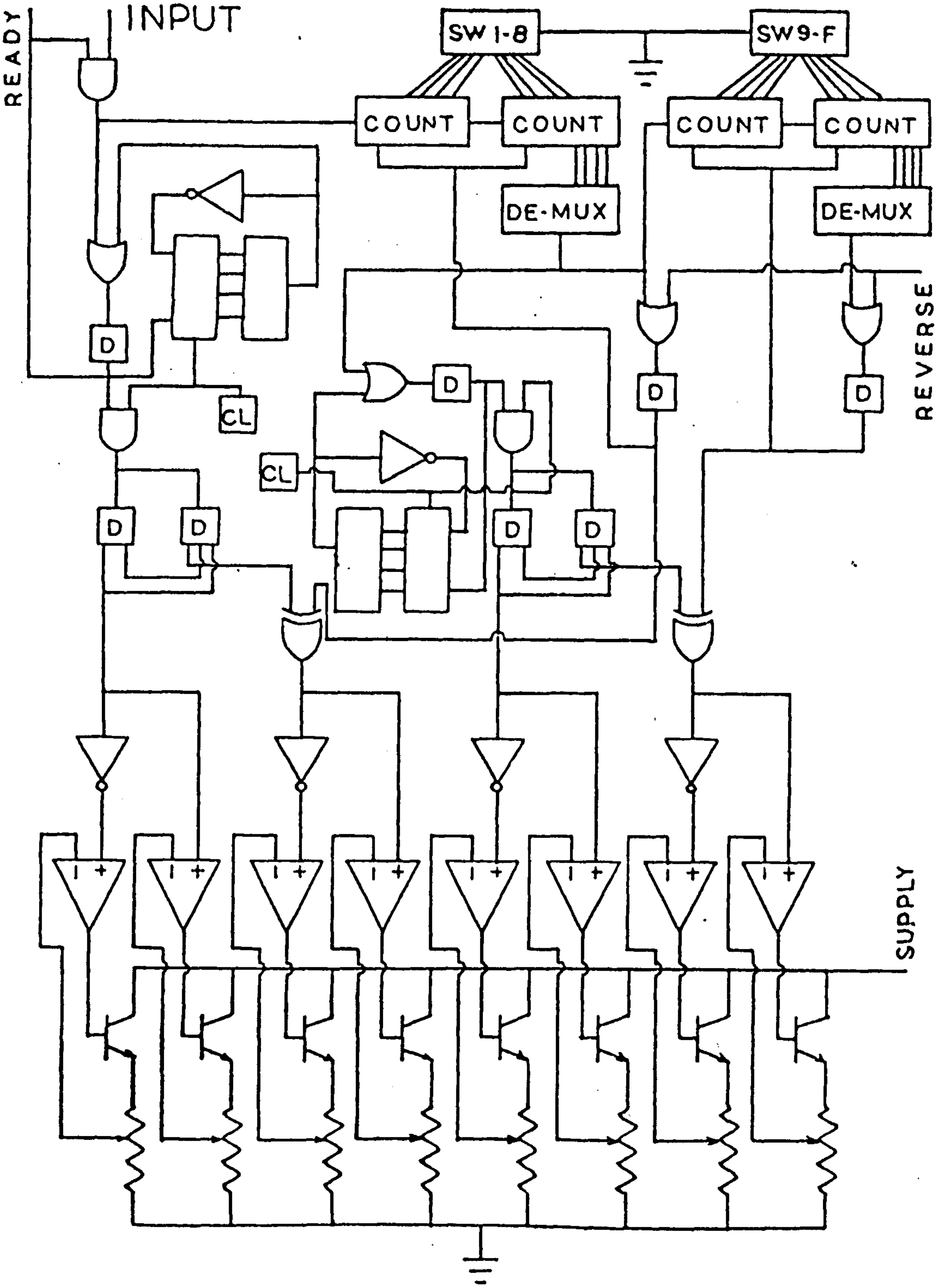
**Figure 7-11: Complete Aiming System**



# CHAPTER 8

# FINAL SYSTEM CONFIGURATION

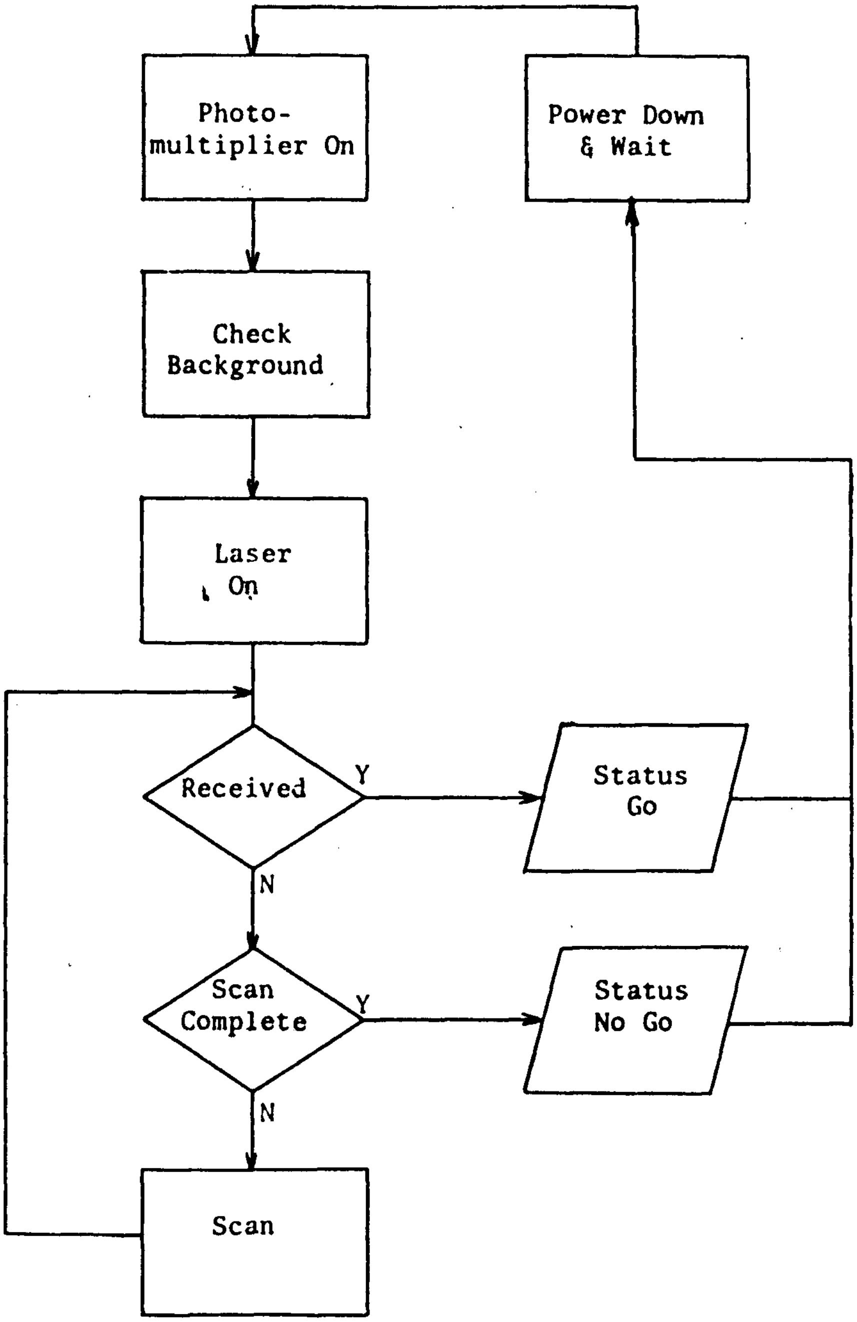
So far the general characteristics of the system have been determined. The laser, aiming, and receiving systems have been designed. The system as it stands now is suitable for testing the feasibility of the laser technique. To turn it into a working system, two things must be done. First, the system must be made automatic. Second, the existing components must be modified for reliability.

## 8.1 Automatic Control System

The automatic control system should be a microprocessor based design because of the variety of functions which the controller must carry out. These functions are outlined in the flowchart if figure 8-1.

When starting up the system, the first step is to power up the receiving system and take a reading of the background light level. Next, the laser is turned on and allowed to warm up (about two minutes). If there is no significant increase in receiver output over the background level, the laser beam is either blocked or misaligned. The beam is scanned across the far wall, checking the light level between scanning steps. When the light level shows a significant increase over the background level, a signal is being received and the system should indicate that the hopper is clear. If no signal is detected after two or three complete scans, it can be assumed that a blockage exists and the system should indicate

**Figure 8-1: Control System Flowchart**



this. Next, the system is powered down until it is time for the next check.

## 8.2 Reliability

Certain Modifications should be added to the present system to increase the reliability and lifetime of the components. The most important modification is to provide adequate shelter from the elements for the laser and the receiver. This protection would take the form of weatherproof boxes for the electronics and enclosures for the laser and photomultiplier.

Another problem is the finite lifetime of the laser. The laser output power degenerates over time regardless of use because of air leakage into the laser cavity. However, this loss of power takes several years; most lasers are guaranteed by the manufacturer to deliver rated power for at least a year. Since the system can still operate at reduced laser power, the laser should only have to be replaced every four or five years.

Another reliability concern is the validity of the go/no-go signal delivered by the system. Failure at any point of the system could cause an erroneous signal to be sent. The solution to this problem would be to include a periodic device check in the operating cycle; this could take the form of a detector to confirm laser output on the transmitter side and an LED to comfirm photomultiplier operation on the receiver side. Finally, some sort of motion detector could be placed on the laser mount to verify the operation of the aiming system.

# CHAPTER 9

# CONCLUSION

This thesis has been a report on a project to devise an obstruction detection system for a coal furnace. The work on the project was done from January, 1981 through June, 1982. A large portion of the project time was spent exploring the acoustic ranging method; several approaches to this method were tried, but the method was finally abandoned. Microwave ranging was considered briefly, but antenna problems quickly eliminated this approach. A laser based system was finally decided upon. The laser system described in this thesis fulfills the project requirements, detecting an obstruction, even though it cannot be used to range the obstruction.

The basic system design involved three steps. These were choosing a laser, choosing a receiver, and designing an aiming system. The choice of laser depended on the transmittance of the optical path; this was calculated to be about 0.6% taking into account the windows and filter. The receiver choice was determined by the sensitivity required to detect the signal transmitted through the furnace. The laser power had to be sufficient to overcome the background light in the furnace, but since increasing laser power increased system cost more than increased receiver sensitivity, the decision was made to use a very sensitive detector rather than a high power laser.

The aiming system was a more straightforward design problem.

The basic requirement was that the system could be run by manual control, but could be easily adapted to automatic control. Cost was also a factor in the design of this part of the system; several companies offer electronically controlled laser positioners, but at a prohibitive cost. The system used was a manual laser positioner driven by stepper motors which could be controlled either manually or automatically. The aiming system has one input and one output. The input is a pulse instructing the system to scan the laser beam one centimeter across the far wall; the output is a ready signal which indicates when the scan is finished. This system can be driven manually (by a switch), by a clock, or by a microprocessor.

Finally, the modifications necessary to configure a everyday working system were discussed. These requirements include automatic start and stop, system status (blocked or clear) readout, self-diagnostics, and proper system packaging (enclosures). With these modifications made, the laser detection system can be made into a useful system.

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# VITA

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