An Optical Positioning System for the Nano-Walker

by

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Abstract

This thesis presents an optical positioning system for the NanoWalker robot. The system is based on a lateral effect photo-diode sensor. The thesis compares various methods of positioning and provides a rationale for selecting the lateral effect photo-diode. It then proceeds with a selection of components for the positioning system. The system is shown capable of resolutions on the order of 5 micrometer, and 10 micrometers over circular areas of diameter 235 mm and 400 mm respectively, with 95% certainty. An explanation of the results is followed by an extension of the results to angular measurements, and velocity measurements. Finally, it is suggested that the size of the system be reduced to gain performance by reducing the signal loss, and the overall positioning area.

Thesis Supervisor: Ian W. Hunter
Title: Professor of Mechanical Engineering

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Chapter 1

Introduction

1.1 Introduction

Current microscopes are based on mounting the sample in the microscope and holding it with some proximity to an optical, or mechanical instrument. In this configuration the components involved in the data acquisition are far smaller than the instrument as a whole. The purpose of the additional material is to fix the sample with relation to the instrument, and provide a means for locating the scanning tip over the scanned surface. Thus, there is an opportunity to miniaturize the system by devising a platform that will bring the sample and scanning tip in contact but does not require the additional material on current instruments. Not only would this reduce the size of the instrument, but also the manufacturing time and the cost. If the new platform were sufficiently small, it would also increase the utility of the instrument by making it possible to move the instrument between samples with minimum effort and time required.

The NanoWalker is such a platform. It is a platform for mounting microscopy instruments, be they optical or mechanical, locating them with respect to the surface, and later moving them to another location to acquire data. The NanoWalker platform is a three legged wireless autonomous robot. The three legs are constructed of piezo electric material. By actuating these legs the NanoWalker can be made to take to walk in sub-micrometer steps, and hence, it can locate the instrument it carries with sub-micrometer resolution. To exploit this ability it is necessary to have a means of measuring the NanoWalker's location that is of comparable accuracy. Since the NanoWalker scans over relatively small areas, but can traverse over a relatively large area, an accurate positioning system would necessarily have a very large dynamic range. To achieve this, the positioning system is broken into subsystems that interface with each other. One system provides the coarse positioning, operating over a large surface area and locating the NanoWalker within micrometers of its final destination. The other system operates over a smaller area and locates the NanoWalker based on surface features in the sample. These two systems interact to guide the NanoWalker to its desired location much in the same way an aircraft pilot interacts with the Global Positioning System. While the aircraft is covering long distances it is guided by GPS. Once it is in view of its destination, the pilot takes over relying on his vision to guide the aircraft directly onto the runway. Since the coarse positioning system will be used to guide the NanoWalker as it walks over a surface it is necessary not only to be able to determine its position, but also its velocity and orientation such that it may be guided to follow a desired trajectory.

The NanoWalker typically carries an instrument to gather data about a site on a surface, or to gather data about a particular sample that it approaches. However, it can also use instruments to manipulate a sample. For example, a NanoWalker fitted with a scanning tunnelling microscope tip can use the tip to scan over a surface and determine its properties, it can also use the tip to pick up atoms and manipulate them.

One goal of the NanoWalker project is to be able to perform atomic scale manipulations on a surface and construct microstructures, a task which could involve several robots. This requires the ability to locate several NanoWalkers at the construction site with atomic scale accuracy. Such positioning accuracy is achieved, as described above, by two positioning systems that interface with each other. The so called Atomic Scale Positioning System (ASPS) is responsible for the fine positioning via surface features, and the Global Scale Positioning system (GSPS) is responsible for coarse positioning of the robot and guidance over the work area.

The focus of this thesis is the development of the Global Scale Positioning System. The system developed for the coarse positioning of the NanoWalker is optically based. It relies on a lateral effect photo diode which employs the lateral effect phenomenon to determine the location of a spot of light on its surface. The thesis proceeds with a survey of available position sensing technologies, the requirements for the NanoWalker positioning system, and the rationale for using a lateral effect photo diode. The experimental setup is then presented along with the criteria for selection of the various components followed by experimental procedures for determining the system's performance, and how it is affected by varying certain parameters, such as ambient light and sample integration time. The results are then presented along with calculations for the expected response of the system. Finally, the conclusions are presented along with recommendations for future work.

The figure on the following page is the NanoRunner. The NanoRunner is a smaller uninstrumented version of the NanoWalker. Although they do not share the same platform, they are very similar, and they operate in the same manner. The NanoRunner is essentially a test bed for the NanoWalker platform.

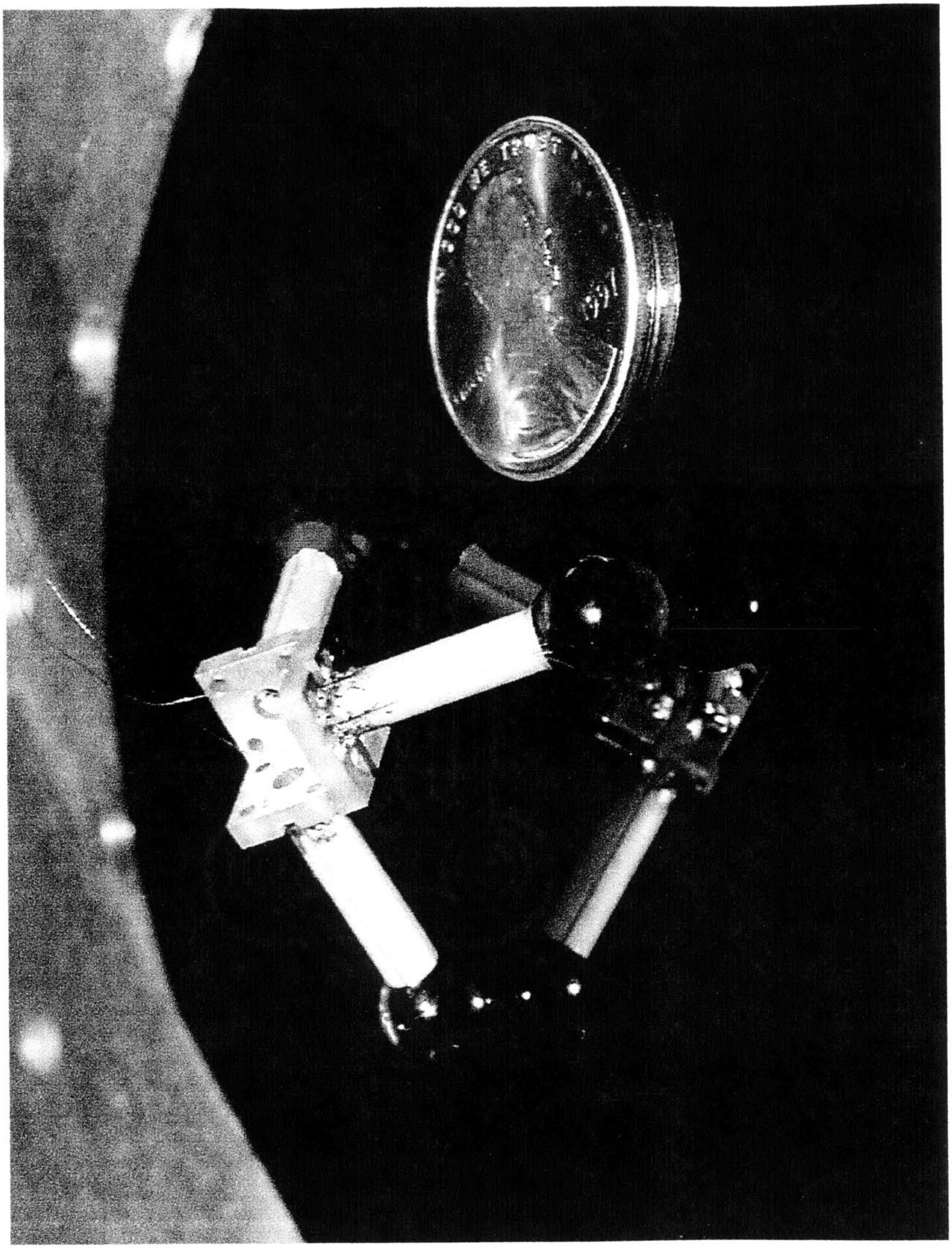

Figure 1.1: The nano-runner. A smaller non-autonomous version of the NanoWalker.

Chapter 2

The Choice of PSD and Its History

2.1 Selecting a Position Sensing Technology

There are a number of different alternatives available for a positioning system. For this application a lateral effect photo-diode was chosen (LEP). The LEP is a semiconductor device that outputs currents proportional to the location of the center of gravity of a spot of light on its surface. The following is an analysis of other techniques considered, and the rationale for selecting a lateral effect photo-diode.

To better understand the overall purpose of a Global Scale Positioning System (GSPS), consider the analogy with an aircraft control tower at an airport. The control tower is aware of the location, identity, trajectory, and intent, of all aircraft in the vicinity at all times. It uses this information to optimize the arrival and departure of flights so as to minimize waiting time and avoid collisions. The system requires no active participation from the aircraft to be located or tracked, and requires no computation, or decision making, on the aircraft's part. The control tower speaks to all aircraft in parallel. The result is a much more efficient means of operation. Decisions are quick and there is no chain effect, as there would be if they aircraft were to talk to each other sequentially. Since the decision architecture is all located in a central entity, it avoids the redundancy of having a decision frame work on board each aircraft, and it frees up the resources of the crew so they can focus on operating their aircraft as directed by the control tower. In much the same way, the GSPS is expected to guide the NanoWalkers and coordinate their motion so as to achieve the most efficient means of interrogating, or manipulating a sample. With this analogy in mind, some requirements for the positioning system are presented.

A suitable positioning system should meet a number of design criteria such that it minimally restricts the design of the NanoWalker and its uses, both in the current version and in future versions. As an example, since the NanoWalker is wireless, it is necessary to minimize power consumption as all power will either come from a battery or through momentary contact with an active power source. Although current battery technology does not provide the energy density to make a battery powered NanoWalker feasible, it is possible that in the future batteries will have the necessary power density, or the power consumption will be reduced. In any case, the requirements for the positioning system carry over.

If the NanoWalker is battery powered, then minimizing the power consumption will increase the battery life, therefore allowing more work time in between charging sessions. In addition to reducing battery consumption, the time taken for the NanoWalker to traverse from one location on the sample to another should be minimized as this will allow more sampling time for a given battery life. Since the Global Scale Positioning System is faster than the Atomic Scale Positioning System, then the NanoWalker should be guided by the GSPS whenever possible. In order to minimize the time when it is guided by the ASPS, the GSPS should be capable of bringing the NanoWalker as close to its destination as possible, thus minimizing the area over which the ASPS must scan for surface features.

Whether the NanoWalker is battery powered, or powered by momentary contact with a power source, the positioning system should require the minimum power from the robot. This means that all detection and computation, if at all possible, should be done outside the robot on the positioning station itself. Minimizing the power consumption is not only important because of the power source, it is also important to reduce the heat dissipated in the NanoWalker.

It is also desirable to shrink the Nano-Walker as much as possible because this will allow a greater number of NanoWalkers to be in a given space at one time, as well as reducing the NanoWalker's mass. This will reduce its inertia, and therefore reduce its power consumption as well as increase its controllability.

Having many robots working simultaneously on one sample will allow a greater number of samples to be taken, and a greater surface area to be scanned in a given amount of time. In order to have multiple robots working on a given sample they must be coordinated such that they do not collide, and they do not overlap, unless it is intended for them to do so. Furthermore, it is necessary to be able to identify the robots individually for a number of reasons. The robots are not identical, some may carry Scanning Tunneling Microscope (STM) tips, some may carry optical fiber, some may carry other instruments. Alluding to the analogy with aircraft control, it is necessary to have a central control tower that is aware of the location, trajectory, and identity of each of the robots, and can direct them much the same way an aircraft control tower directs aircraft at an airport. In order to direct the NanoWalker, it is necessary to be able to predict its actual trajectory and provide a correction based on a comparison with some desired trajectory. Thus, the system must be able to find not only position, but also velocity and orientation of a given robot.

Being able to identify individual robots is important for reasons other than knowing what instrument they carry. It is important so that re-charging can be coordinated in case a battery powered robot is used in the future. For all of these reasons the control tower must be able to identify each robot and obtain information on it's position and trajectory. It is highly desirable to have a single positioning system that can be used to locate all of the robots, identify, and provide information about their trajectory (i.e. orientation, and velocity). Furthermore, the system should be modular, such that additional robots can be added to the workspace, and immediately they can be identified and tracked with no necessary additions to the positions system, again, much the same way an air traffic radar tower operates. Planes fly into the control tower's airspace, and they are located and directed without need for modification of the location system. From the previous discussion a number of requirements for the positioning system become apparent. These requirements place constraints on candidate technologies. To summarize, below is a list of attributes that a positioning system should have In order to be suitable for this application:

1- As accurate as possible.

2- Require minimal hardware on the robot itself, if any at all.

3- Require minimal power consumption from the robot

4- Allow differentiation between individual robots

5- Require minimal computation on board the robot.

6- Be minimally invasive to the working area and sample.

7- Be able to position multiple robots simultaneously.

Some of the options considered for the GSPS are presented below. Given the above constraints, the lateral-effect photo diode, or PSD (Position Sensing Detector) as it is often called, is the best, and only option that satisfies the constraints. Following is a comparison of different alternatives for positioning that will illustrate why this is so.

Different alternatives for Global Scale Positioning System:

1-Dead Reckoning

2-Interferometry

3-Radar

4-Gyroscopes

5- CCD observation

6- Lateral Effect Photo diode

1- Dead Reckoning

Dead reckoning provides a rapid way of estimating the position, however due to imperfections in the robot legs, or assembly, or irregularities in the walking surface, errors accumulate, and the result is dead reckoning does not provide the resolution needed. The positioning system is needed in part to provide feedback to the robot so that it may correct deviations in its course that rise as a result of errors in position accumulating as the robot walks. Additionally, dead reckoning requires the robot to perform all calculations and transmit the information back to the central control. This both increases the calculations the robot must perform, and increases the data it must transmit, which in turn takes more power to transmit. Dead reckoning can be used for short distances on the periphery of the work space outside the reach of the positioning system, where distances are short and high accuracy is not necessary.

2- Interferometry

Interferometry seems at first an attractive option because it has the desired dynamic range, and can certainly provide the accuracy needed, however, it has other forbidding limitations. For each interferometer, a laser is required. To measure position in two dimensions, each laser must be mounted either on a linear stage, or a rotary stage. These lasers would require very accurate tracking algorithm in order to follow the robots on the surface, adding further complexity to the system. A reflective surface would be needed on the robot to reflect the lasers back to the interferometer. The reflection would have to be directed back at the laser, regardless of the incident angle, in order to make the measurement. This reflective surface in itself would be very complicated. It would need to reflect directly back to two separate interferometers, as if it had two retro-reflectors, but also, the reflection would need to be independent of the rotation of the robot. This inherently means that an interferometric positioning system for this application cannot make an angular measurement. If for some reason a laser were to lose contact with its NanoWalker, it would be very difficult to find it again. With several robots on one work space, inevitably the robots will cross each others laser paths causing the laser to lose track of its intended robot. There is a relatively large amount of data processing associated with calculating the robot's position from the information taken on the interferometers, and then making the interferometers track. Finally, the system is very costly, and not scalable.

3- Radar

Although small scale radar is an attractive option, it doesn't provide the desired resolution, and has other problems. With radar there is no way to identify individual robots in a work space where there are many robots working. Unlike an airplane, the NanoWalker has no direct means for identifying itself to the positioning system. It cannot inform the tower of its position, as it has no independent positioning system. Furthermore, if at all possible, it is desirable to avoid sending any sort of signal or field towards the working area as it may disturb certain samples, cells, for example.

4- Gyroscope

Gyroscopes and other inertial guidance systems are clearly not practical. They add weight and size to the robot, have relatively high power consumption, as well as raising the power consumption of the whole robot as a result of the increased mass.

5- CCD Observation

It is possible to use a camera to detect position [1]. That has the advantage that is completely passive i.e., it requires no input from the robot what so ever. However, a video camera is limited in both resolution and sampling rate. Typical Video cameras sample at 30 frames per second, and their resolution is limited by pixel size. In this case, for a work space half meter a in length, the resolution of a CCD is given by

$$Resolution = p\langle\frac{500}{l}\rangle, \qquad 2.1$$

where p is pixel size in micrometers, and l is the length of a side of the CCD in millimeters. In this case, for a $20\ mm \times 20\ mm$ CCD (the size of the PSD used) with a pixel size of seven micrometers, which is typical, the maximum theoretical resolution would be 175 micrometers. Although it is possible to improve this resolution by using pixel interpolation, it greatly increases the computation required, additionally, CCDs still present other disadvantages. If a CCD is used, complex image processing software would be necessary to determine the position of a NanoWalker. It would be difficult to distinguish between individual robots without placing some distinguishing feature on each NanoWalker. Even with individual markings, the software to distinguish one robot from another would be complex. Finally, with a maximum sampling rate of 30 Hz, a velocity measurement is not feasible. The maximum speed of the NanoWalker is 200 mm/s. At maximum speed, the NanoWalker would cover 666 micrometers between two samples taken by the CCD. This makes it difficult to simultaneously measure position, and velocity. Additionally, with only 30 samples per second, it would take a long time to integrate to improve the signal to noise ratio. These problems can be overcome by using a lateral effect photo-diode.

6- Lateral Effect Photo diode

The workings of a lateral effect photo diode, or so called Position Sensing Detector (PSD), will be discussed in the next section. For the purposes of explaining why it was selected as a position sensor it is sufficient to know that it is a light sensitive semiconductor surface which when struck by light outputs currents proportional to the location of the centroid of the light spot. A few years ago, it would have been difficult to use a PSD for this application, however, recent advances in the manufacturing have made it possible to use these devices. Specifically, they can now be manufactured with high linearity, low capacitance, and uniform resistivity over the surface which makes them practical for use in position sensing systems such as ours. With a dynamic range of a million to one (manufacturer's claim) [1], the theoretical limit on resolution imposed by the PSD is half a micrometer over a half meter work space.

$$Resolution = \frac{Range}{DynamicRange}. \qquad 2.2$$

In practice the resolution is usually not limited by the PSD but by other factors such as the optics, the electronics, and the data acquisition system. The manufacturer claims a typical resolution of 1 to 2 μm at the surface of the PSD which translates to 25 to 50 μm at the working surface. Given the claimed dynamic range though, it is possible to improve on this accuracy with high quality optics and electronics, and careful shielding of the system from possible noise sources. A PSD is one of the most accurate, and repeatable devices that can be used for such a positioning system. Evaluating how well the PSD matches each of the design criteria previously stated, it is found that it fits quite well. The only hardware requirement on the NanoWalker is a light source, such as an LED. This can be very small, on the order of a half millimeter by a half millimeter. The power requirement from the robot is also minimal. It takes a fraction of a watt to power the LED and it is only turned on intermittently, when the robot needs to be located, mainly for guidance to or from a scanning area. The NanoWalker already has an LED mounted to it that is used for communicating with the main control center. Because this LED cannot be independently controlled, it is not used as the primary LED for positioning. This will be discussed in detail in Chapter 4.

Today's PSDs have extremely high bandwidth. This makes it feasible to distinguish between individual robots based on the frequency at which they flash their LEDs. Multiple light spot tracking using a single PSD has been demonstrated by Qian *et al.* [2] and by

Narayanan *et. al.* [3]. By modulating the light transmitted from each robot at a different frequency, it is possible to separate the locations of individual light beams based either on amplitude by taking the Fourier Transform and considering power only at a given frequency, or on phase by considering the phase difference induced by travelling different lengths in the PSD[3]. Both these methods will be discussed in the results section. For this section, suffice it to say that each robot can be identified by its frequency signature, and given the high bandwidth of the PSD, it is feasible to do this for a number of robots.

The computation required by the robot is minimal. Only a command of when to turn on the LED and when to turn it off and at what frequency, is necessary. The frequency can be constant, and can serve as an identifier of the robot, so the only information needed is "LED on" or "LED off." The PSD itself is inherently passive. Unlike radar it does not transmit and receive, it only receives. There is no chance of disturbing any sample by something being emitted from the PSD.

Finally, the PSD system has the advantage of being scalable to more than one robot with no hardware additions. The number of robots that can be detected is limited by the bandwidth, and saturation power (light from too many robots could cause saturation) of the system. There must be enough separation in frequency such that one robot can be distinguished from another. Given the high bandwidth of the PSD (up to 10 MHz, according to the manufacturer), the number of robots is likely to be limited by the bandwidth of the electronics.

Because of all the previous reasons, the PSD is an ideal choice for this application. It is worth mentioning that with the PSD's of only a few years ago, it would have been much more difficult to accomplish this task. In fact, there would have been no simple way to create such a positioning system using any technology. Given the quality of today's PSDs, it is possible.

2.2 The Lateral Effect

The lateral photo-effect is the basis of the lateral effect photo-diode. It was first observed by Schottky in 1930 [4,5] while working with a Cu-Cu_2O diode. Schottky found that the photocurrent from the terminal on the diode decreased exponentially as the light source moved away from the terminal. He explained this by reasoning that if the fractional loss of current in every unilluminated strip of oxide was constant, and the oxide has a constant finite resistivity, then the observed exponential variation would follow[6]. It was twenty seven years later that Wallmark, who is often credited with the invention of the PSD, used this effect to measure the position of a spot of light [7].

There are several available designs for a PSD, the most common being simply a large area silicon p-n photo-detector [8]. When light strikes the surface of the detector, a current is generated which then flows through the bulk resistance of the semiconductor producing the later field effect. If the resistance of the semiconductor sheet is uniform, the current through each electrode decreases exponentially as the distance from the centroid of the light spot increases. Connors [9] has shown that if the resistance of the semiconductor can be assumed uniform, then the solution for the one dimensional differential equation governing current out of an electrode is

$$i = I\left(\frac{\sinh[\alpha(L-d)]}{\sinh(\alpha)}\right), \qquad 2.3$$

where i is the current out of a given electrode, I is the total current, L is the distance between two opposing electrodes, and d is the distance from the centroid of the spot of light the electrode, and α is the Lucovsky parameter[10]. Given the recent advances in semiconductor manufacturing technologies, the linearity of these devices has increased minimizing the Lucovsky parameter. As the Lucovksy parameter approaches zero, the PSD approaches linearity and Equation 2.3 becomes for a one dimensional PSD

$$i \cong I\left(1 - \frac{d}{L}\right). \qquad 2.4$$

Using the above equation, we can see that on a two dimensional PSD, the location of a spot of light is given by

$$P_x = \frac{L}{2}\left(\frac{x_1 - x_2}{x_1 + x_2}\right) \quad , \qquad 2.5$$

where is P_x the x-axis location, and x_1 and x_2 are the currents off the +x and -x electrodes, respectively (see diagram below). Similarly, the y-axis position, P_y is given by

$$P_y = \frac{L}{2}\left(\frac{y_1 - y_2}{y_1 - y_2}\right). \qquad 2.6$$

This result for a linear PSD can also be seen directly from the schematic below

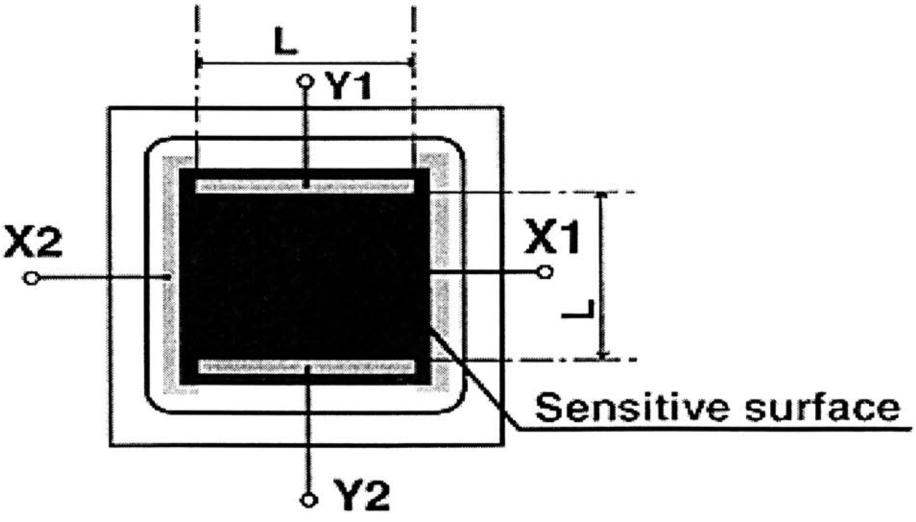

Figure 2.1: Schematic of currents from two dimensional PSD (Copied from On-Trak application notes).

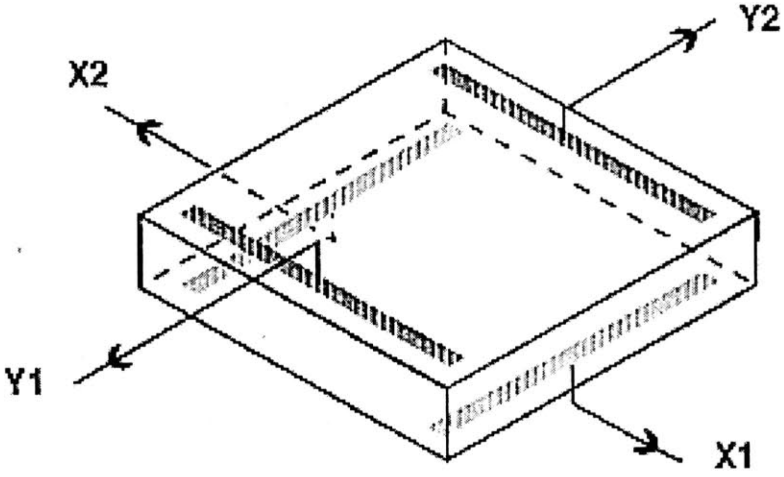

Figure 2.2: Schematic of actual PSD (Copied from On-Trak Application notes).

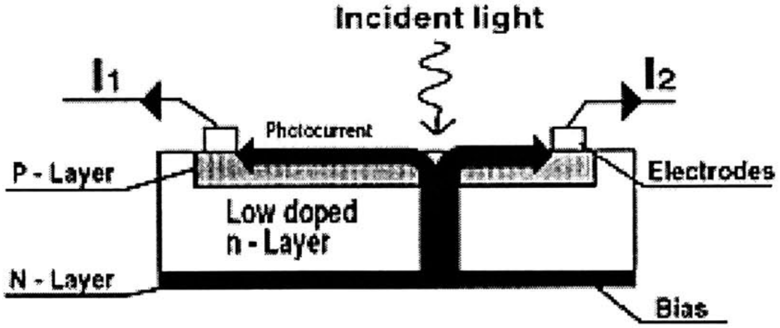

Figure 2.3: Depiction of incident light on a PSD (Copied from On-Trak Application notes).

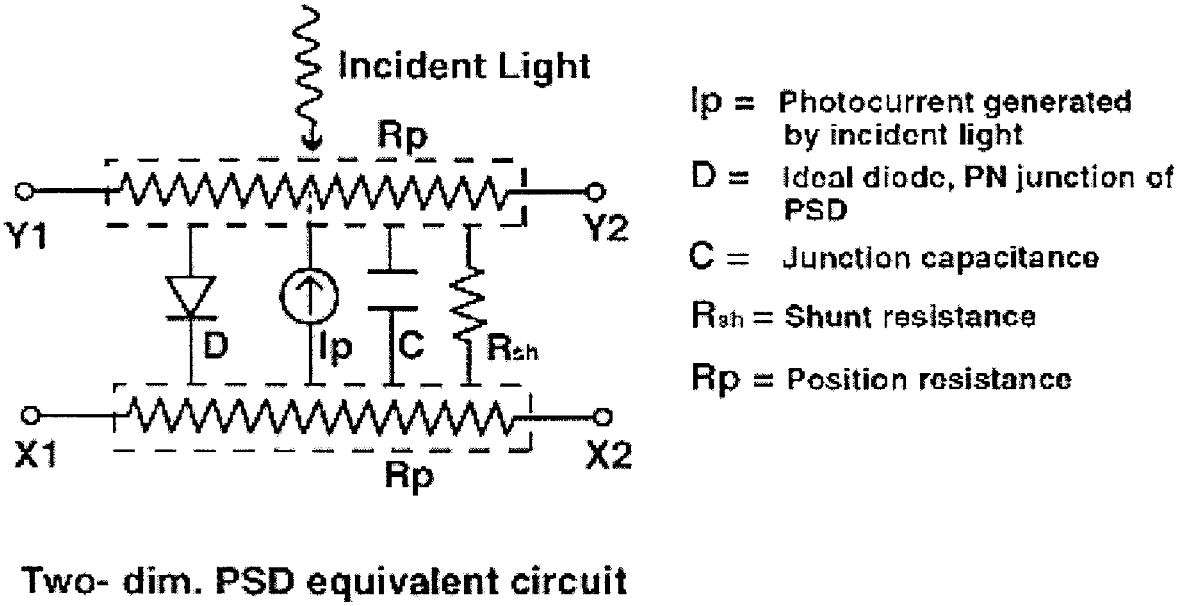

Figure 2.4: Circuit model for two dimensional PSD (Copied from On-Trak Application notes).

2.3 A Brief Survey of PSD Applications and Uses in the Literature.

Although available for many years, recent advances in PSD technology have greatly increased their applications. PSDs are now used in various forms of noncontact measurements from sensing the surface quality of roads, to guiding welding robots to measuring surface flatness, and automotive body profiles, to measuring the motion in a golf swing [PSD school notes] Most applications do not require the resolution demanded here.

Marszalec *et al.*[11] have reported on using PSDs in a triangulation probe configuration to measure three dimensional surfaces with errors on the order of millimeters. Marszalec et al. have also reported on a similar triangulation PSD based system for robot vision to pick up drums of paper with similar accuracies. For most applications, accuracy on the order of millimeters is sufficient. However, in some applications, such as the one presented here, higher accuracy is required. Other PSD application demanding high resolution are surface flatness and squareness measurements, such as in machine beds and machine tools.

Schaefer *et al.* [8] have obtained resolutions of up to 0.05 mm with a setup very similar to the one presented here. PSD's have also been used in optical spectrum analyzers. The light is passed through a collimator and prism then through a slit onto the PSD surface. By knowing the position of the slit, and determining the position light incident on the PSD the wavelength can be determined.

There are many other interesting applications of PSD's. The purpose of this section is not to provide a comprehensive enumeration of all applications, but rather to give a familiarity with the technology and its uses.

Chapter 3

Experimental Setup

3.1 Overview of the Setup

First an overall view of the setup is presented, then each of the components. The work space of the nano-walker is a circle half a meter in diameter. The PSD is mounted inside a housing one meter away from the working surface. It is at this height because the infrared communication system needs to be mounted one meter away from the transceivers. If the PSD were further away it would mean the infrared transmission system would create a blind spot in the middle of the work space. If the PSD were closer, it would block the path of the communication system. As it is, the PSD and the communication transceiver are mounted side by side.

The PSD images the work space through a Nikon lens. Tests were performed with two lenses, an 85 mm f/1.4 and a 50 mm f/1.8. The output of the PSD is amplified through four Analog Devices 549 (AD549, Analog Devices, Norwood, Massachusetts) low noise operational amplifiers configured as transimpedance amplifiers. The transimpedance circuit feeds into a PCM slot on a computer through a 16-bit data acquisition board. The output of the X channels, and the Y channels are then added subtracted and divided digitally. To reduce noise pick up as much as possible, the circuit is powered by batteries and the computer is powered through an isolation transformer. The addition and subtraction are performed digitally to minimize the analog operations, and therefore minimize the opportunity for noise pickup.

In order to test and calibrate the system, a light source is needed to simulate the NanoWalker. It is necessary to be able to control the position of this light source such that the system can be calibrated. A Hewlett-Packard HSDL-4220 infrared (see Appendix B)

LED is mounted on a two axis precision linear stage setup to simulate the NanoWalker. This LED is of the same type as the LED used for the infrared communication system.

The motion stages are each fitted with Renishaw (Hoffnan Estates, Illinois) linear optical encoders with 1 micrometer resolution, and are controlled via Compumotor (Parker Hannifin, Ukiah, California) stepping motors connected to Compumotor Zeta drives and a Compumotor 6200 controller. This allows precise positioning of the LED simulating the NanoWalker in any desired location, and then measuring that location. Hence, a means of calibrating the position sensor.

The motion stages are bolted onto an optical mounting table. The PSD and data acquisition system are mounted on an L-shape construction of 76 mm (three inch) aluminum box extrusion with 6.4 mm (0.25 inch) wall thickness. The fixture is welded together and bolted to the optical table on which the motion stages are fixed. It is positioned such that the center of the PSD is as close as possible to the center of the two axes. The following pages present a schematic and a picture of the experimental set up.

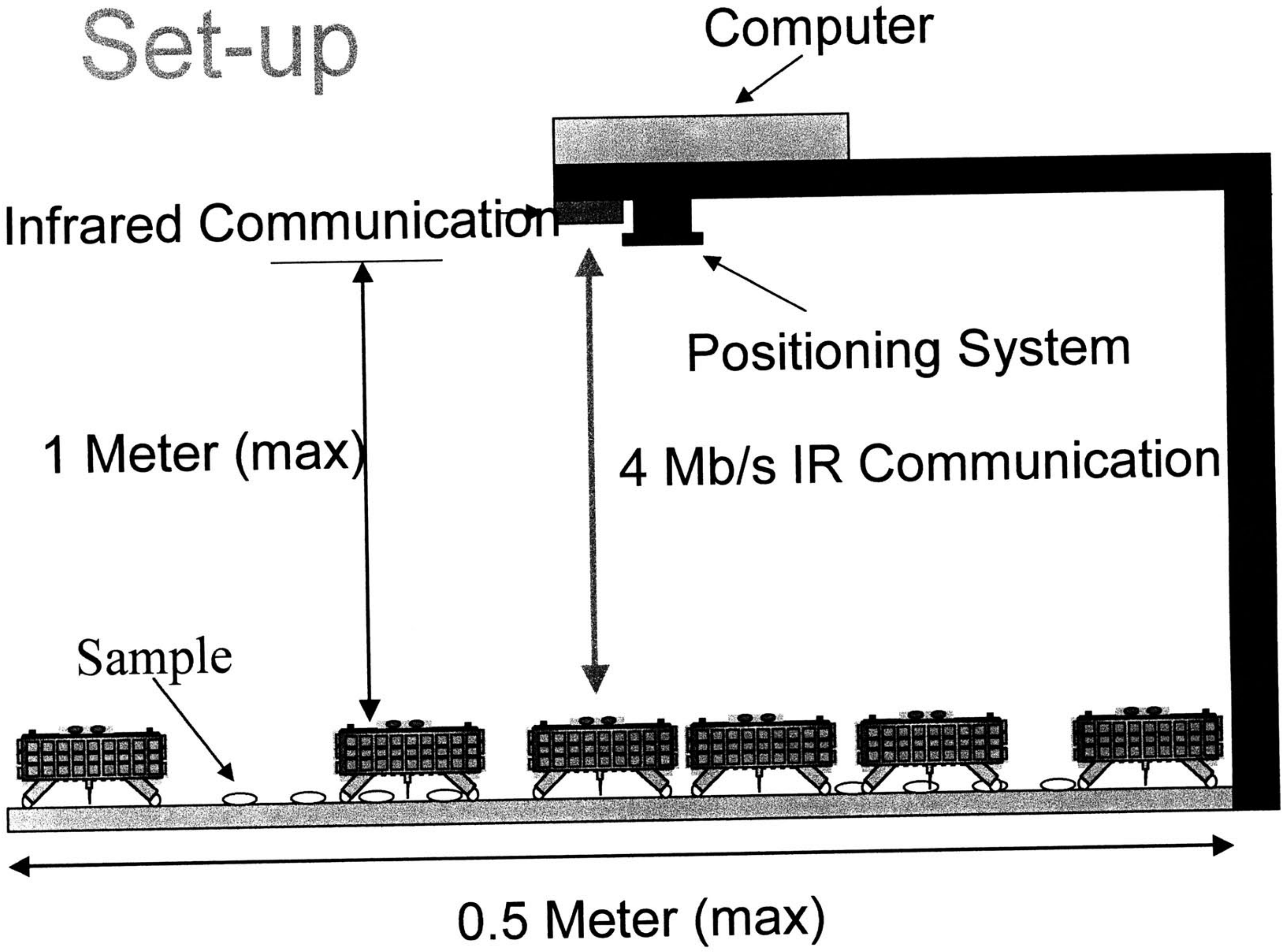

Figure 3.1: Experimental Setup (Courtesy Dr. Sylvain Martel).

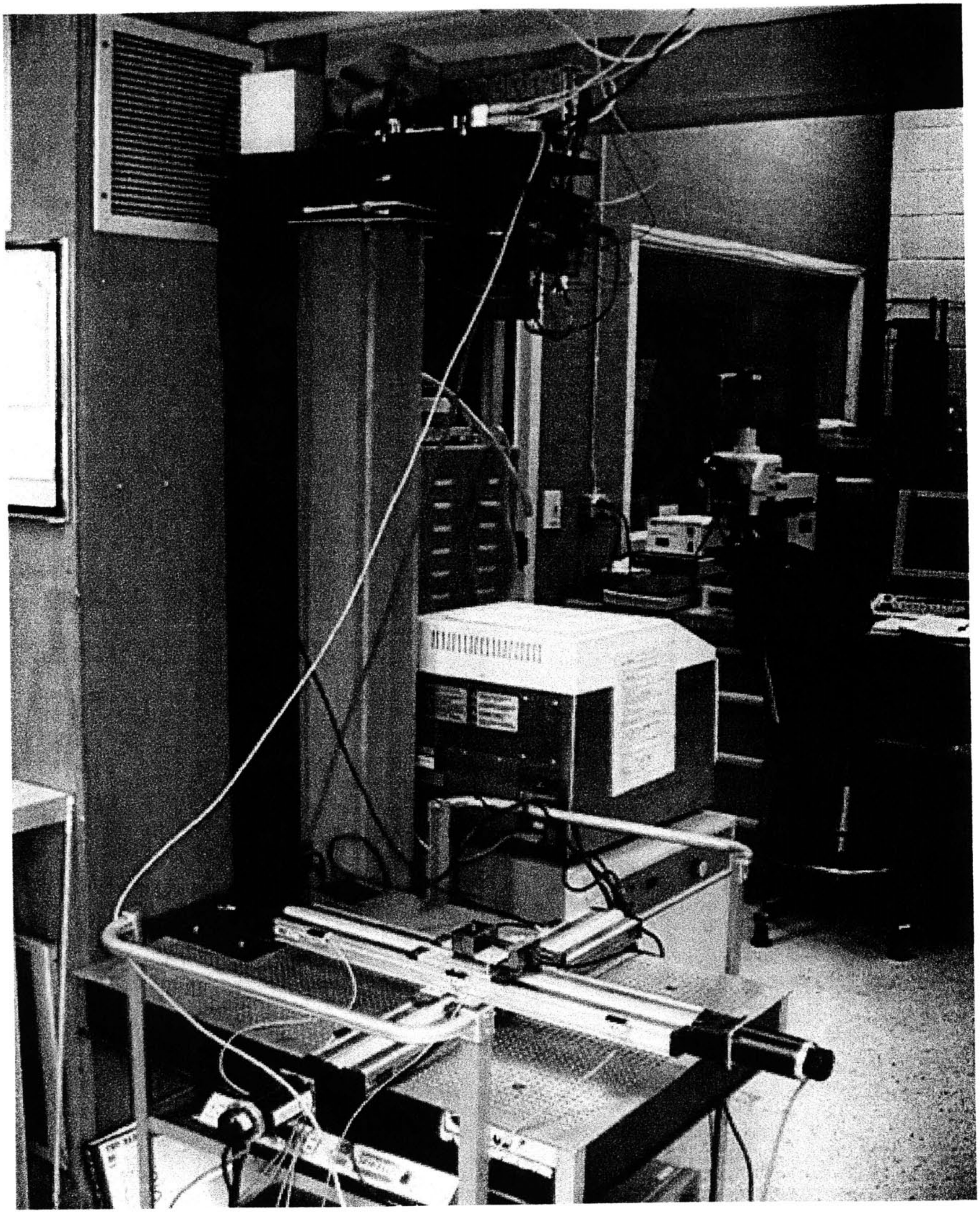

Figure 3.2: Experimental Setup.

3.2 Selecting the Components

A. Selection of a PSD

Position sensing detectors are manufactured in several sizes by a number of manufacturers. Among the most reputable are Hamamatsu, UDT Sensors Inc., and Sitek. There are other companies that manufacture PSD's on custom order, however these produce and stock them, and the technology represents a central part of their expertise. Hamamatsu was ruled out early because they claim linearity of 1% to 2%, which was less than other manufacturers. UDT, while a strong competitor, did not seem to have the base of expertise that Sitek had. Thus, aSitek PSD was selected. Sitek Laboratories are the original manufacturers of the PSD. Founded in 1976 by Professor J. T. Wallmark, who is often credited with the discovery of the PSD, as mentioned before, they are reputed to manufacture PSD's with the highest accuracy and linearity. The decision to purchase a Sitek PSD was influenced by speaking to others in the field who have used them for other applications and reported excellent linearity and accuracy.

In order to measure two axis position, a two dimensional PSD was selected. There are many sizes of PSDs, and not surprisingly the smaller ones exhibit better linearity and accuracy than the larger ones. However, given our large work area, we could achieve the maximum resolution over the greatest portion of the work area by selecting a larger PSD. The PSD is mounted behind a Nikon lens through an extension ring. Since the characteristics of the lens change as the light shines through different parts of the lens (i.e., there is variation in distortion, etc.) the measurements taken do not actually reflect the PSD's linearity, but rather the overall linearity and accuracy of the system, which is what this study is interested in determining.

In order to minimize the noise in the system, the PSD was operated unbiased. While this decreases the responsivity, it also decreases the noise, and the overall result is a gain in the signal to noise ratio.

B. Selection of the Optical Components

The working surface on which the NanoWalker is to be positioned is imaged onto the PSD surface through a lens. The surface on which the NanoWalker is to be positioned is half a meter in diameter, and the PSD is $20\ mm \times 20\ mm$. Hence, the requirements for the lens were:

1- A minimum focusing distance of less than 1 meter.

2- Focal length such that at 1 meter height it maps the entire half meter working surface onto the PSD.

3- The lens should have as large an aperture as possible in order to let through as much light as possible and increase the signal to noise ratio.

4-The lens should be as planar as possible, and provide the minimum of distortion

A standard 35 mm photography lens was chosen because the picture frame they are designed for is closest to the size of the PSD, and they are ready available from high quality manufacturers with large apertures. The area of a picture frame on 35 mm film that the lens was designed for use with is $24\ mm \times 36\ mm$. The viewing angle of the lens is quoted for the diagonal, which is 43.26 mm. The PSD is 20 mm on each side. In order to select a lens that will cover the desired area, it is necessary to calculate what the viewing angle is for the PSD. Applying basic trigonometry it can be seen that the viewing angle for the PSD is

$$\Theta = 2\left[tan^{-1}\left(\frac{l}{r}\tan\left(\frac{1}{2}\alpha\right)\right)\right] , \qquad 3.1$$

where *l* is the length of a side of the PSD, *r* diagonal for which the viewing angle is quoted, in this case 43.266 mm, α is the manufacturer's quoted viewing angle.

The result is that only the center portion of the lens is used. However, in this case that is advantageous because the center portion is likely to be the most distortion free.

To cover the half meter work space from a height 1 meter, the PSD should have a viewing angle Θ of 28 degrees. This means the lens should have a maufacturer's quoted viewing angle of 56.8 degrees. There are no commercially available high quality 35 mm lenses with this viewing angle. The lenses with the closest viewing angles are a 50 mm lens, and a 35 mm lens with viewing angles of 46 ^{o} and 63 ^{o}, respectively. These translate to PSD viewing angles of 22.6 ^{o} and 31.8 ^{o}, respectively. Choosing the 50 mm lens would mean that the PSD would only image a working space of 400 mm in diameter, hence an annulus of 50 mm width would not be part of the positioning area. Choosing the 35 mm lens would mean that the PSD would see a work space of 570 mm in diameter, hence an annulus of 35 mm in diameter would be wasted space. This wasted space means that the working space is mapped onto a smaller area of the PSD resulting in a loss of resolution. Given the emphasis on increasing the resolution of the system, the 50 mm lens was chosen. The outer 50 mm ring can be navigated using dead-reckoning. The accuracy and resolution of positioning in that area is not critical, and the area is small enough such that errors accumulated from dead-reckoning should be tolerable.

Since the NanoWalker is a relatively small robot, it may not be necessary to have such a large work space for it. In an attempt to further increase the resolution of the system, an 85 mm lens was also tested. The 85 mm lens has an effective viewing angle for the PSD of 13.4 ^{o}, which means a work space of 235 mm in diameter. The 85 mm lens was chosen because it is the next length up from 50 mm that is available in large apertures (f/1.4). Nikon lenses were selected because of they are generally accepted as having very high quality optics. No tests were made to characterize the lens as part of this thesis. This would be both time consuming and futile. Given that the lens is of high quality, characterizing it in detail is not useful. It is the overall function of the system, lens and PSD, that we are interested in.

By projecting a circular work space onto a square PSD, the corners of the PSD are avoided. It is the corners were the greatest non-linearity is observed, and by following this design, that area is avoided at the price of having another area outside the PSD surface.

C. Selection of a Light Source

The NanoWalker has an infrared communications LED mounted on to it. The original design of the positioning system intended the use of the communication signal from this LED for positioning. However, this is less than optimal, since this LED cannot be controlled, and cannot be turned on and off as desired. Hence, it would be difficult to distinguish between individual robots. Additionally, since it is transmitting at 4 Mb/s, it is difficult to observe and record digitally. Finally, all NanoWalkers transmit at 4 Mb/s, which makes it impossible to differentiate between them based on a frequency signature. In order to make an angle measurement, it is necessary to have a second LED on the robot (to give two points which can be connected to form a line in the direction of orientation). Given that a second LED must be mounted in any case, it is desirable to use the second as the primary location LED, and use the infra-red transmitter as the second LED for measuring angular orientation. This will be discussed in greater detail in Chapter 4.

The maximum sensitivity of the PSD between 870 and 940 nm. In order to achieve the maximum signal, it is desired to have a light source that emits very close to this value. The HP HSDL-4220 LED is essentially the same LED as used in the Infrared Data Association (IrDA) communications system. It uses TS AlGaAs technology to provide high output power at a peak wavelength of 875 nm, and has an illumination angle of 30 degrees (see Appendix B).

In order to increase the robustness of the system, and minimize the effect of ambient light, a filter was installed. The filter cuts out ultra-violet and visible light, but passes infra-red wavelengths (cut off wavelength 780, maximum transmission achieved by 820). Hence the effect of ambient light on the system is greatly reduced.

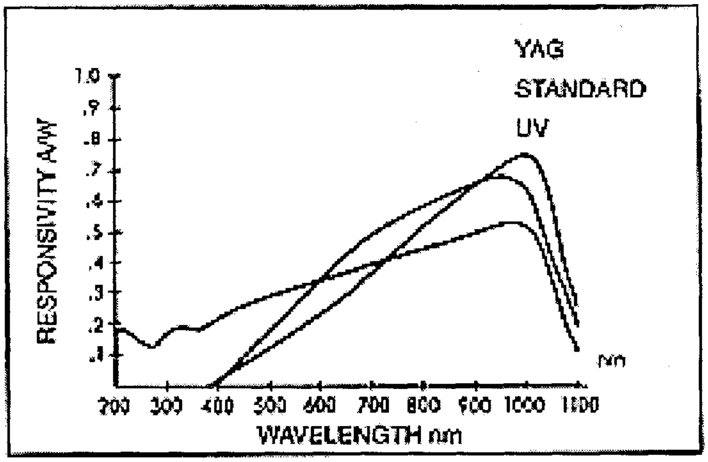

Figure 3.3: PSD Responsivity Curve (Copied from On-Trak Application Notes).

D. Selection of Mechanical Positioning Components

The LED is mounted on two linear stages. Daedal 500 mm precision stages were selected in order to cover the entire working range of the robot. They are driven by stepping motors with 25000 steps per revolution. The lead on the ball screw in each table is 5 mm/revolution. This results in a potential positioning resolution of 0.2 micrometer. In reality it is often difficult to control the motors to make one step. Potential errors in positioning are resolved by having a 1 micrometer Renishaw encoder mounted on each stage. This resolution is sufficient for the desired application. While the precision of the stages is such that the encoders are seldom needed, The stages are computer controlled, and programmable so that they can be positioned to a desired location, then have a measurement taken. Thus we have the ability to position the LED source anywhere in the desired half meter diameter work space, and measure its location with 1 micrometer resolution.

E. Data Acquisition and Processing

There are four currents generated from light falling on the surface of the PSD. Typically the resolution of a PSD system is not limited by the PSD itself, but rather by the optics and the electronics associated with it. Currents output from a PSD are added, subtracted, and divided, as in Equation 2.5, and 2.6, to yield an X-axis and a Y-axis position. Purchased with the PSD was an electronics box that had inside it electronic circuitry which performed the subtraction, summation and division, and output an analog X position, and Y position. This electronics box was found to be too noisy. The components used were not of the highest quality, nor were they optimized to achieve the maximum resolution, or maximum performance. Furthermore, the division was performed in analog

To improve the results as much as possible, an ultra low bias current circuit was built to amplify the signal from the PSD. The circuit consisted of four transimpedance circuits. The key element in this circuit is the operational amplifier. An Analog Devices AD549 operational amplifier was selected because it provides an extremely low input bias current, input offset voltage, and input offset drift. It also has a very high common mode impedance, essentially ensuring the input current is independent of the common-mode voltage. The input bias current is typically 60 fA. These characteristics make it ideal for the current application.

The AD549 amplifiers were arranged as shown in the schematic on the following page.

Because of the relatively low output currents of the PSD (approximately 10 μ A), large amplification is needed. These circuits were built with a 500,000 times gain.

The voltage output from the circuit was taken directly into an 18 bit (true 16 bit) A/D converter. The subsequent additions, subtraction, and division were all done digitally. Sampling was at 50 kHz, and integration time was varied. The maximum theoretical resolution of the system with a true 16 bit A/D converter is 15 micrometer over a half meter range. This takes into account that fact that the A/D converter is bipolar (converts positive and negative voltages) while the PSD is inherently unipolar (current will always go into a terminal, or out of a terminal, but will never switch signs).

While it is possible to add and subtract in analog form with high accuracy, the possibility for noise pick up very large. It is necessary to convert the signal to digital in any case in order to use the information from the positioning system to control the nano-walker. Since a digital conversion is inevitable, performing it early on in this case minimizes noise, which is the primary limit on the performance of the system. In a system limited by A/D resolution, analog computation would be advantageous, however in this case it provides no clear advantage. Once converted to digital, data collection is via a Visual Basic program which writes to a Matlab file. Matlab is then use for data manipulation and analysis.

As is the case with many highly accurate systems, the performance of this system is inherently limited by noise and thermal drift. Much effort has been spent minimizing noise, and many features of the design are aimed distinctly at that goal. Previous designs of this system had cables connecting the PSD to an amplification box which then connected to a desktop computer to perform the A/D conversion. The cable connections were found to pick up too much noise, so they were shielded. While this offered some improvement in the noise pick up, it was still not satisfactory. The amplification circuit described above was manufactured and mounted directly on to the PSD minimize noise pick up, and amplify as close to the PSD as possible, thereby minimizing the noise that gets amplified maximizing the signal to noise ratio.

One major source of noise was the computer. It is not clear exactly what the source of noise was, whether it was pick up in the frame of the computer, or noise generated by the switching in the computer. The motherboard was removed from the computer, and separate from all possible noise generation sources. Mounted on a board, and well grounded, with only a hard drive and a A/D conversion card connected, it was placed immediately above the PSD in order to perform the digital conversion as close as possible to the signal source. The final configuration has the amplification circuit connected to the PSD via a shielded gender changer, and circuit connected to the data acquisition system through very short shielded wires.

3.3 Procedures

This positioning system is to be used to obtain three types of results.

1- A Position

2- An Orientation

3- A Velocity

All three are measurements of position, they are only processed differently. The system is not actually capable of making a direct measurement other than position. However, with several positions in known time intervals, a velocity can be inferred. Likewise, with two position measurements representing two points on a given robot, an orientation can be inferred. There are certain parameters of the system to be determined. Its resolution, its repeatability, the dependence of resolution on radial location, and the dependence on number of samples averaged over. To establish the resolution of the system, the motors toggle back and forth between two points. With each travel, the motors shorten the distance between the two points, and taking measurements at each point. This produces a plot of output versus change in position, in essence a resolution measurement. Repeated over the surface of the PSD this gives an indication of the resolution as a function of location on the surface. When the change in output falls to the noise level, that is the limit on resolution. Because of the noise generated by the motors, the are turned off when data is being taken. As a result, the motors move to the nearest pole, and therefore cause a positioning error of at most 12.5 micrometers. Over large distances, this error is no significant. To test the resolution of the system, the motor is stepped manually from one pole to the next. There are 200 poles in the motor, so a motion from one pole to the other corresponds to 25 micrometers in stage translation. The output for the 25 micrometer translation is then compared with the output for different displacements to determine linearity, and it is compared with the minimum detectable output change to determine resolution. Tests were performed with a DC current of 95 mA through the LED. This is the limit of DC current that can be put through the LED.

Chapter 4

Results

4.1 Positioning Results

The Sitek PSD was found to be extremely linear. There was no deviation from linearity detected except on the very edges of the work space. With the 50 mm lens, position resolutions of 10 micrometer, and 15 micrometer with 95%, and 99.7% certainty, respectively. For the 85 mm lens, resolutions of 5 micrometer, and 7.5micrometer were calculated with 95%, and 99.7% certainty, respectively. With the current setup, it is not possible to directly measure these results. These results were obtained, as discussed in the procedures section, by manually moving the stepper motor from one pole to the next, an increment of 25 micrometers, measuring the response and dividing by 3.92σ and 6σ to obtain the resolution 95% and 99.7% certainty, respectively. The output of the PSD was linear with displacement to within the noise of the system, i.e. the output for 2 mm travel, is twice that for 1 mm travel, which is 40 times that for 25 micrometer travel. With the true 16 bit A/D card operating in bipolar mode the maximum measured resolution should be 7.2 micrometer. Hence, it seems the system is reaching the limits of the A/D card. Still, because of the noise levels, a very large number of samples was taken to obtain this result (40,000).

With a higher resolution A/D, which is also slower, this sampling would be prohibitively long. As a result, it is recommended that the noise and thermal drift be reduced before a higher resolution data acquisition system is used. Lower noise levels will allow fewer samples with the higher resolution data acquisition card, making it more practical.

The resolution of the system is limited by noise, however, the noise is by and large gaussian white noise. This was verified for low frequencies by measuring the noise spectrum on a Hewlett -Packard Dynamic Signal Analyzer Model No. 3562A. It is further evidenced by the improvements in repeatability with increasing sample size. Since the Dynamic Signal Analyzer is only capable of making measurements up to 40 kHz, the output of the system was also connected to an oscilloscope to verify that the noise is in fact Gaussian at high frequencies. While the motors are off, this is true. As a result, the signal to noise ratio can be improved by increasing the number of samples taken for each position measurement, i.e., increasing the integration time. Plots of resolution versus number of samples, and resolution versus integration time are provided below. The integration time limits the maximum sampling frequency of the system. There error expected based on the number of samples taken is given by

$$error = Z\frac{\sigma}{\sqrt{n}}, \qquad 4.1$$

where Z is determined by looking up in a table of areas under a standard normal curve depending on the degree of confidence desired, σ is the standard deviation of samples taken, and n is the number of samples taken. For 99% confidence intervals, Z = 2.575, and for 95% confidence intervals, Z = 1.96 [12]. The plots on the following pages are shown for real sampling frequency, which is the frequency at which a position data point is given, after the integration, not the frequency at which the A/D board samples.

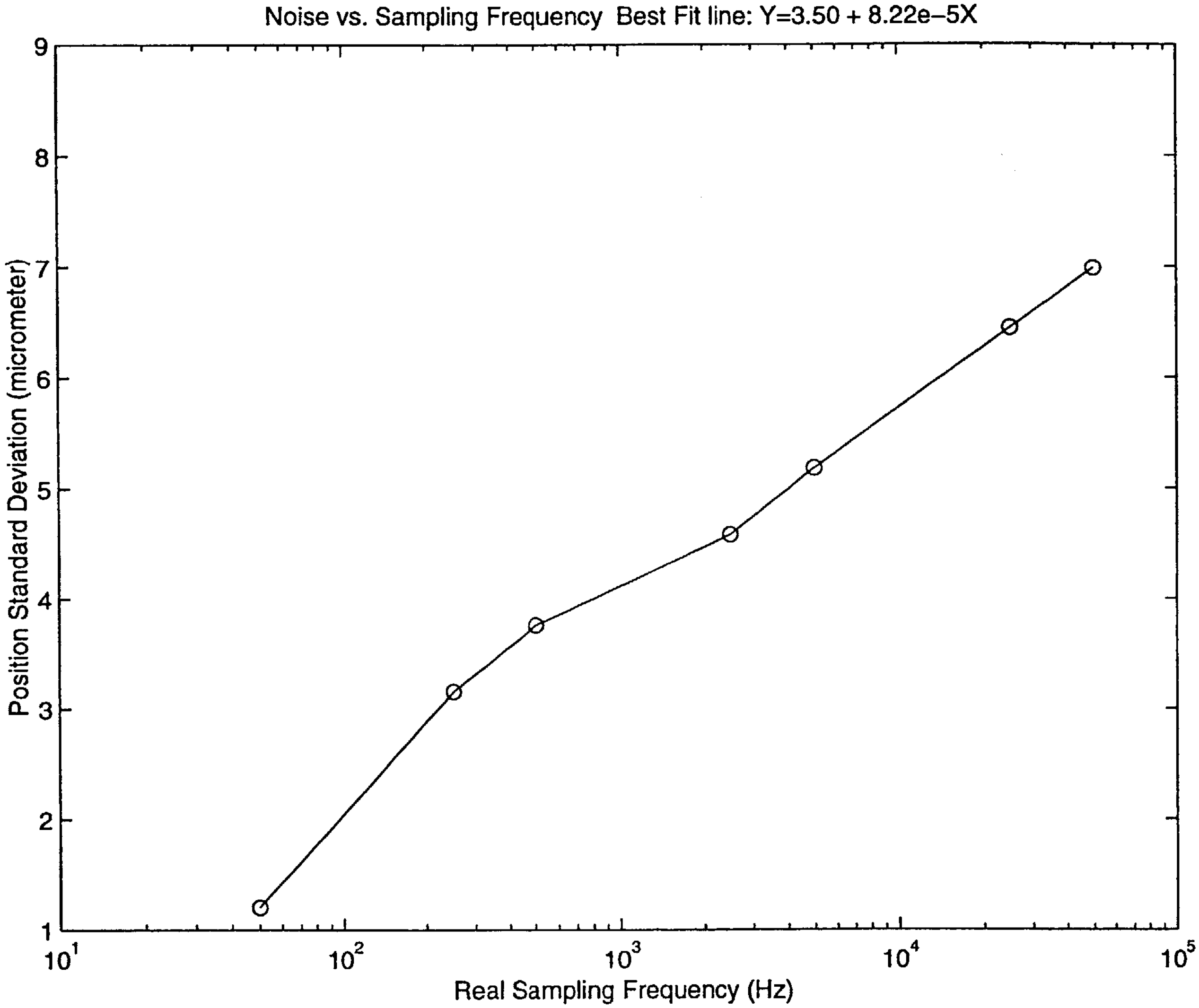

Figure 4.1: Position Standard Deviation as a Function of Real Sampling Frequency.

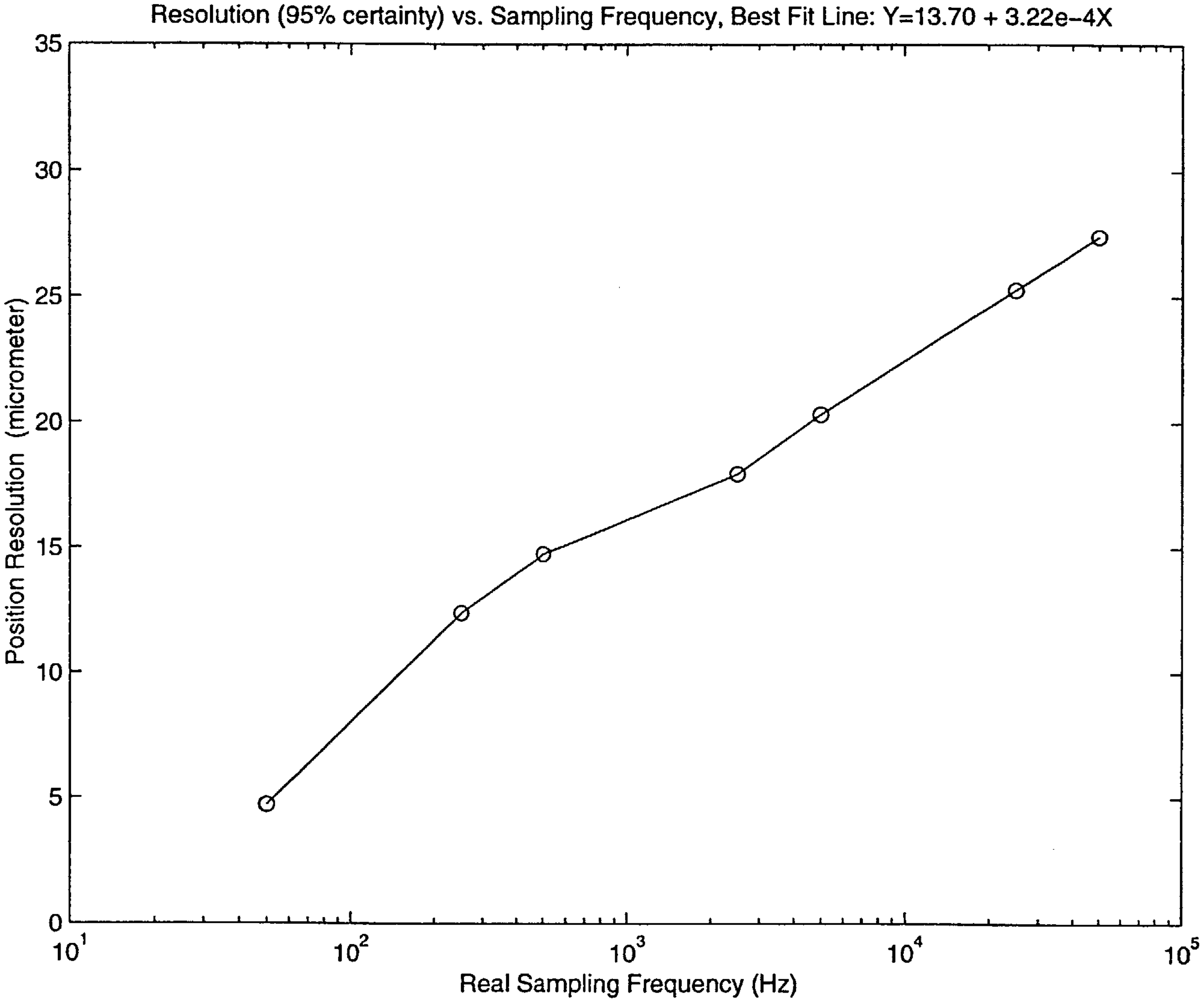

Figure 4.2: Resolution as a function of Real Sampling Frequency.

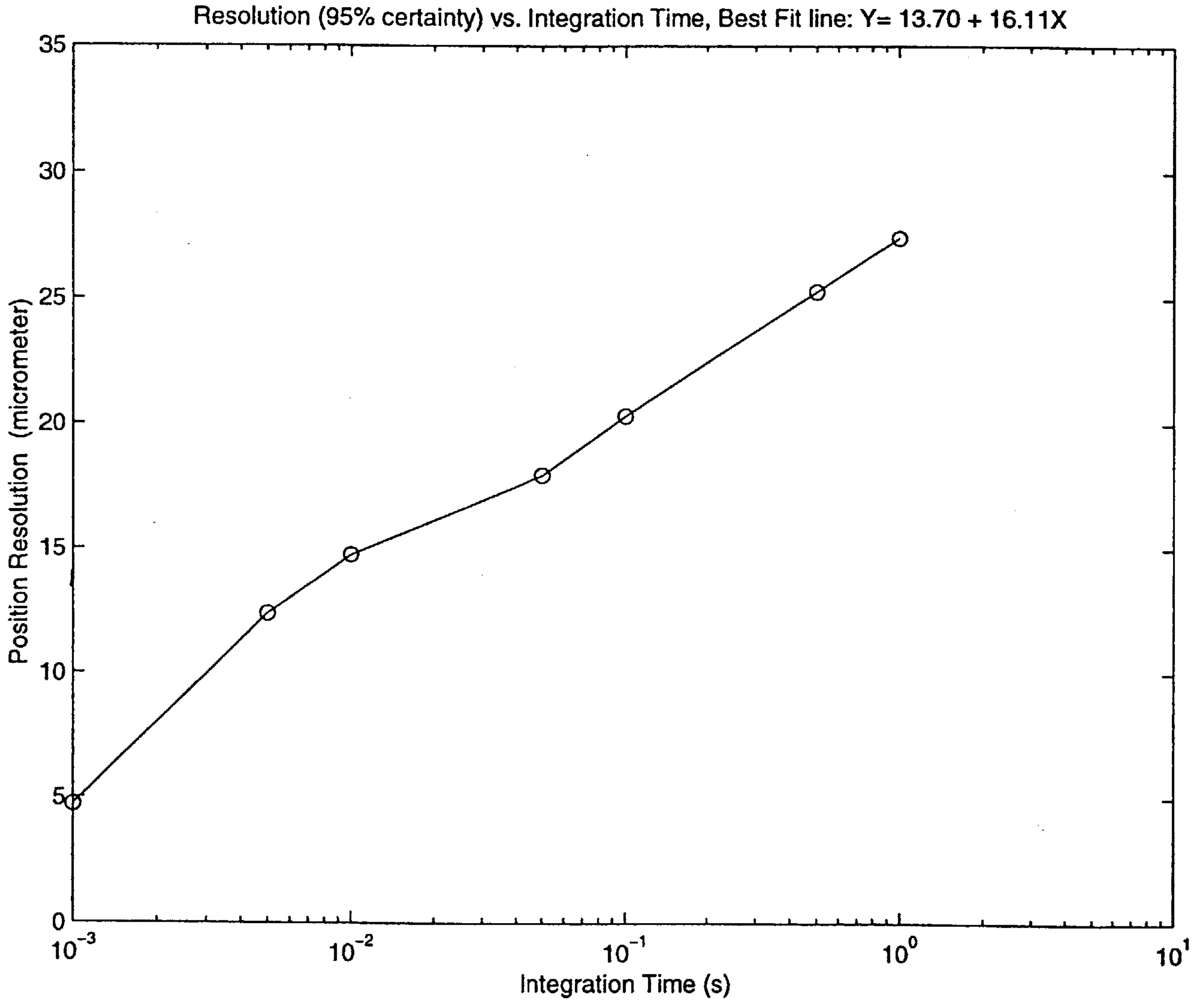

Figure 4.3: Resolution as a function of Integration Time.

In order to optimize the system, its is necessary to vary in the integration times. For a robot which is moving rapidly, maximum resolution is not of primary importance, nor is it achievable. If long integration times needed for high resolution are used, the samples will not match because the robot will have moved during sampling. Shorter integration times necessary for a fast robot inherently give less resolution. However, a rapidly traversing robot needs only coarse guidance, it is only when the robot is near its final location that high resolution is required. At this point, the robot has practically no velocity, and is only creeping. Hence, long integration times can be used to improve the resolution of the system when it is needed. At its maximum speed of 200 mm/s, and a sampling time of 100 ms, the NanoWalker would have traversed 20 mm in a single sample, completely defeating the purpose of obtaining a large number of samples.

The resolution of the system could potentially be increased by using a higher resolution A/D. This will not guarantee better resolution, as there are other limits, such as the sharpness of the lens, and the inherent limits on the PSD itself. The manufacturer claims a dynamic range of a million to one for the PSD, but states that this is almost never achieved because of limitations of the optics and electronics. A dynamic range of a million to one would yield resolution of 0.5 micrometer over a half meter space. A more realistic dynamic range of 100,000 would yield a resolution of five micrometers. Schaefer et al.[8] have demonstrated a position resolution of 1 mm over a working area of 1.22 meters in the central region of the detector.

Resolution is maximum at the center of the detector because at the center there is the maximum signal to noise ratio, the most light is being picked up from the LED, additionally, there is a minimum of distortion due to nonlinearity. The optical lens also produces its best images in the center, where distortion is a minimum. Given the quality of the lens used for this application, distortion should be a minimum. All these factors combine to give the best possible results at the center of the PSD.

4.2 Angular Results

A PSD can only make one kind of measurement, that is a position measurement. In other words, the only information that can be obtained from a PSD is the location of weighted center (the center of mass) of a spot of light on its surface. This inherently means that it cannot provide an angular measurement by virtue of any sort of asymmetry in the LED's lighting pattern, or anything of the sort, the PSD will simply output the position of the centroid of the light spot. There is no way to determine from this one measurement the orientation. Furthermore, if the LED is not symmetric, then the position measurements will have a systematic error that results from the center of the LED not being in line with the center of the spot of light produced by the LED. Yet, as mentioned before, in order to plot a trajectory for the robot, it is necessary to know its orientation. The only information given by an LED mounted on the robot is the location of a single point on the robot. However, if the locations of two separate points on the robot are known, then it is possible to determine the orientation of the robot by connecting the points. For this reason, it was chosen to mount two separate LEDs on the robot. By knowing the location of each LED it is possible to determining the orientation of the robot by simply drawing a line that connects them. It is not sufficient though to know the location of the two LEDs mounted on the robot, it is necessary to know their identity. In other words, a line drawn through the robot places the robot on a given line, but does not indicate which way it is facing on that line. It would be akin to having a compass needle with no arrow on it. You could be oriented on a line running from the North to the South pole, but have no way of telling if you are facing North of South (without external data from the Sun for example). In order to distinguish the direction the NanoWalker is facing, the LED's must be labelled, for example, "head" and "tail." Thus, the line from tail to head to always orient the NanoWalker.

Taking a line passing through the NanoWalker, from simple trigonometry the angle, Θ, enclosed between this line and the horizontal axis has a sin and cos of

$$\sin\Theta = \frac{y_1 - y_2}{d} , \qquad 4.2$$

$$\cos\Theta = \frac{x_1 - x_2}{d} , \qquad 4.3$$

where x_1, x_2, and y_1, y_2, are the horizontal axis locations, and the vertical axis locations, respectively. d is the distance between the two LEDs. It can be seen that as d increases, the error in the angle measurement decreases, but the resolution in angle measurement decreases by the same amount. For a $d = 10$ mm, angular resolutions on the order of 0.15 degrees are obtainable. The error is found by taking the cosine of possible error in position measurement divided by d, where the error in position measurement is found as described in the previous section.

4.3 Determining a Velocity

A velocity is obtained simply by dividing the distance the NanoWalker covers by the time in between measurements. Given the high accuracy with which time intervals can be recorded, the error in velocity measurement is likely to be due only to errors in position measurement. At its maximum velocity (200 mm/s) the accuracy of a velocity measurement taken once every second would be accurate to 0.1 mm/s. This result is obtained based on averaging over 10 samples for each position measurement, the error in position, with 99% certainty, will be less than 25 micrometer. In the time taken for 10 samples, the NanoWalker will have traversed 40 micrometer. Taking a worst case approximation, adding these two, the error is 65 micrometer in each position measurement, or, 130 micrometer for both. Since the measurements are 1 second apart, then the error in velocity is 0.13 mm/s. In a similar manner, the error can be determined for any velocity, by selecting the number of samples over which the position is to be averaged, calculating the error in position measurement, then dividing the error by the time interval.

The velocity measurement is simpler than the angle measurement. Knowing the location at time t = 0, and at time t = t, the velocity can be found simply as follows

$$v = \frac{\sqrt{(x_2 - x_1)^2 + (y_2 - y_1)^2}}{\Delta t}. \tag{4.4}$$

This has the disadvantage that it does not provide a direction to the velocity. A robot travelling from $x_{1,}\ y_1$ to $x_{2,}\ y_2$, is indistinguishable from a robot travelling from $x_{2,}\ y_2$ to $x_{1,}\ y_1$. It is possible to distinguish between them, without resorting to the orientation, by resolving the velocity into its two components

$$v_x = \frac{x_2 - x_1}{\Delta t}, \tag{4.5}$$

$$v_y = \frac{y_2 - y_1}{\Delta t}. \tag{4.6}$$

4.4 Positioning Multiple NanoWalkers

As mentioned before, there is a need to position several NanoWalkers on the working surface. A number of authors have reported on the positioning of multiple light spots on a PSD [2,3]. There are generally two methods for accomplishing this. The first and simplest method, is by sequentially turning on and off the light sources aboard the NanoWalkers.. There are some advantages, but its disadvantages ultimately suggest the use of another method. The second method is by modulating the light source from each NanoWalker at a different frequency, then demodulating the signal from the PSD to obtain the position of an individual light spot.

Sequentially switching the NanoWalkers on and off can be computational simple (e.g. switch on once every second), however, it does not allow more than one NanoWalker to be positioned at a given time. If long integration times are used to increase the accuracy of the positioning, it may mean several seconds between two position measurements on a single robot. Trying to optimize the system such that fast moving robots not needing high accuracy positioning are positioning more frequently, with less accuracy, while slower robots needing high accuracy positioning are positioned less frequently, but with greater accuracy complicates the system and still does not solve the problem. This problem only becomes greater as more NanoWalkers are added to the system. Furthermore, the switching causes transients in the system which necessitates a reduction in power to avoid saturating the detector. The reduction in power in turn leads to a loss in measurement accuracy. Increasing the time between measurements to allow transients to die out makes the system even slower. For these reasons, a method that allows simultaneous positioning of the NanoWalkers is desirable.

Qian *et. al* [2], as well as Narayanan *et. al* [3] have reported on using different methods to allow the simultaneous positioning of multiple light spots. Borrowing technology from the communications industry Qian *et. al* have used a modulation method to allow multiple light spot detection. With each light spot being modulated at a different frequency, the output of the PSD is a superposition of the signal from each light source. Demodulating the output provides the individual positions of each light source.

With the NanoWalkers, different robots require different positioning accuracies at different times. Hence, different integration times. Using this method, each robot can have its desired integration time without affecting the others. This is accomplished by running the data acquisition system at its maximum sampling speed. For robots requiring maximum speed sampling, the position from that sample is then fed into the control system immediatly. For robots requiring slower sampling but higher accuracy, their position is held, and averaged with a number of subsequent measurements, then the average is passed to the control system. While this technique offers high linearity, and high resolution, it requires complex signal processing circuits. It also requires complex modulation circuits to synchronize the modulations and demodulations.

The number of NanoWalkers that can be detected by this method is limited by the bandwidth of the system. In the past the PSD was the limit on the bandwidth. Given today's PSDs, the bandwidth of the system is likely to be limited by the circuitry. The data acquisition board used for A/D conversion operates at 50 kHz, hence the fastest modulation frequency should be no more than 25 kHz, and preferably closer to 15 kHz. It is not unreasonable to expect to be able to position 15 NanoWalkers [2].

In order to avoid saturating the detector, the maximum power from each beam, P_{max} must not exceed P_{sat}/N, where P_{sat} is the saturation power and N is the number of robots being detected. For the LED used in the experiments presented here, this limit is higher than the bandwidth limit, and hence is not of concern. Care should be taken, however, in the future when increasing the number of NanoWalkers, as improved circuitry increases the bandwidth. Also, should the LEDs used here be replaced with stronger LEDs, this may become a concern. It would necessitate the power out of each LED be regulated.

Narayanan *et. al* have reported on the position detection of multiple light spots using a phase method [3]. When a sinusoidal light excitation strikes a PSD surface, the output will also be sinusoidal and with the same frequency, but with amplitude and phase varying with the position of the light beam on the PSD surface [3]. Currents travelling different lengths in the PSD experience different time delays, and thus there is a position dependent phase difference between the outputs. Detection of this phase difference allows the position to be inferred. Using this method, the output is not dependant on the intensity, hence there is no need to normalize by dividing by the sum of currents. The circuits used for phase detection are simple and inexpensive, simplifying the signal processing needed. Taking the output of the PSD and applying phase detection (frequency division multiplexing) the position of several light spots can be found independent of each other. The limits to the number of robots that can be detected still apply.

Chapter 5

Conclusions and Recommendations

5.1 Limitations of the System and Suggestions

The system is mainly limited by the noise levels and thermal drift. Any attempt to improve the system performance would have to focus on increasing the signal to noise ratio, and decreasing the thermal drift. The performance of the system could also be increased by reducing the work area. A number of suggestions are made to improve the performance, they are listed below then each is discussed in detail.

1- Increasing output from the LED

2- Increasing view factor into lens

3- Decreasing the possibility for noise pickup

4- Decreasing the operating area.

Increasing the output from the LED comes at the cost of more power consumption. By modulating the LED, the currents passed through it can be increased, and hence the output power increased, but run for shorter periods of time. The trade off must be made between keeping the LED on for longer periods of time to allow long integration times, and flashing it brighter for shorter periods of time. Switching to a higher power LED would allow it to be on for longer periods of time with high current, but this increases the

Increasing the view factor into the lens would mean that the lens gathers more of the light emitted by the LED. This can be done by bringing the lens closer to the LED. This would also shrink the positioning system. However, bringing the infrared transmission system closer to the working area will reduce its effective range. A concave lens mounted on the transmitter would solve this problem by increasing the viewing angle. A similar lens should be mounted on the robot. Short of this, a new communication LED should be used. The underlying circuitry need not change, only the plastic package around the LED. Halving the distance between the working surface and the lens would quadruple the light into the lens, thus requiring less amplification, and therefore less noise at the output of the amplifiers.

Although the PSD was run in unbias mode, it maybe beneficial to experiment with biasing the PSD only slightly. Applying a bias increases the sensitivity, but also increases the noise. A bias on the order of 15 V, as suggested by the manufacturer, results in too much noise for this application [See Appendix A].

The whole data acquisition system could be wrapped in shielding, thereby creating a Faraday cage, and decreasing the chance for noise pick up. It is unclear whether or not this will provide a real benefit.

Finally, decreasing the operating area would mean that a smaller area can be projected onto the PSD surface, therefore, reducing the magnification of the optics, and so taking better advantage of the resolution at the surface of the PSD. A 50 mm lens held at 0.5 meter above the working surface would result in a working surface of 200 mm in diameter, roughly the size of the working surface for the 85 mm lens used here, but with 4 times the amount of incoming light as the 50 mm used in this set up. A 35 mm lens at 0.25 meter above the working surface would result in a 140 mm diameter working surface, and would have 16 times the light input. Using Equation 3.1, and a manufacturer's quoted viewing angle of 84^{o}, a 24 mm lens at 0.25 m height would have a working space of 500 mm, but 16 times the light into it of the current set up. It is not recommended to use lenses shorter than 24 mm, as distortion becomes a problem in even the best of lenses. Perhaps the best means of increasing the performance of the system is a combination of reducing the size, as well as reducing the work space. It should be noted that when bringing the lens closer to the LED than the minimum lens focusing distance, it becomes necessary to change the distance between the lens and the PSD. In other words, it is no longer possible to focus the LED on the PSD while holding the PSD where photographic film would be held behind the lens. Using the lens maker's equation, the distance from the lens to the PSD can be determined by knowing the focal length of the lens, and the distance from the lens to the LED. The lens maker's equation is

$$\frac{1}{\mu}+\frac{1}{\nu} = \frac{1}{f}, \tag{5.1}$$

where μ is the distance from the lens to the LED, ν is the distance from the PSD to the lens, and f is the focal length of the lens.

Because the PSD provides the center of gravity of an incident light spot, whether the light spot is exactly in focus or not is not critical. However, a tightly focused light spot should provide better resolution. Further, a tightly focused light spot can be positioned closer to the edge of the PSD with less loss in lineatiry, and the spot will not truncate until it is off the PSD. This minimizes the chance of errors becuse of a spot that is patially in a non-linear area, or that is partially off the PSD.

5.2 Conclusions

A positioning system for the NanoWalker has been presented and tested. The system is highly repeatable and capable of position resolutions on the order of 10 micrometers or better. The main limits on the performance of the system are noise and thermal drift. The thermal drift is almost entirely due to the drift in the electronics rather than the mechanics. This is evidenced by the short times over which the system can drift (a few minutes), if the electronics are not well insulated. Insulting the electronics greatly increases stability, and the data taken here were with some insulation on the electronics. The system is capable of providing an angular measurement, and a velocity measurement both based on position measurements. Further improvements can be achieved by reducing the size of the system and reducing the area over which the NanoWalker is to be positioned. WIth this scaling, and careful elimination of noise, it may very well be possible to achieve resolutions of one micrometer.

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Appendix A

High Linearity Position Sensing Detector

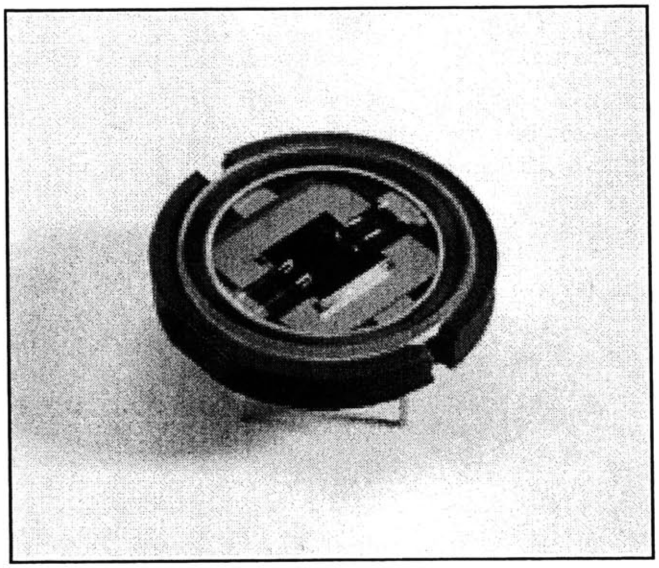
2L2SP - two dimensional PSD

The SiTek 2L2SP PSD functions according to the Lateral Effect-Photodiode principle. It is an analogue device and therefore displays excellent position resolution. The resolution is determined by the system signal-to noise ratio.

The 2L2SP is operated in the biased mode.

Typical applications include: distance and height measurement, alignment, position and motion measurements and vibration studies.

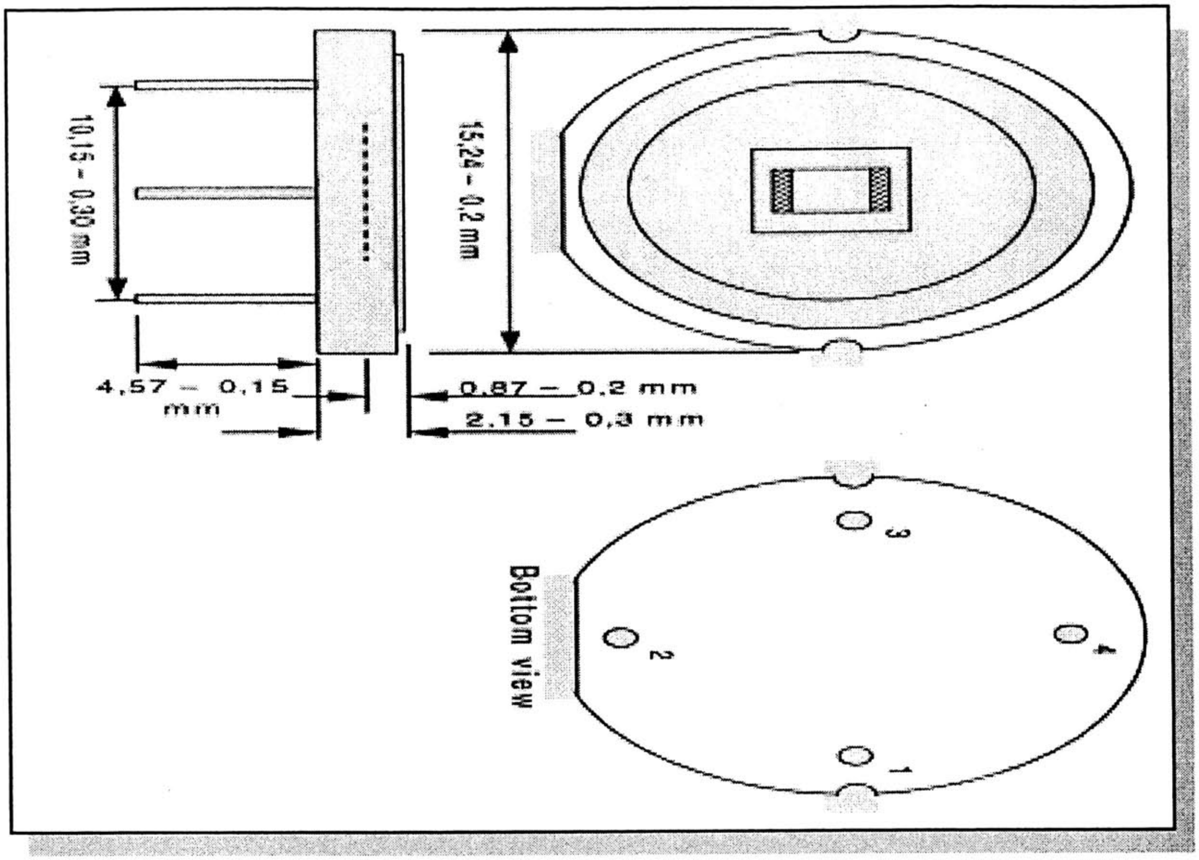
Special UV- or YAG-enhanced and Nuclear versions are available.



Parameter	Symbol	Min.	Typ.	Max.	Unit
Active area			2 x 2		mm^2
Position non-linearity			0,3	1,0	%(±)
Detector resistance	R_{det}	7	10	16	k ý
Dark current	I_d		50	200	nA
Noise current	I_{noise}		1,3	2,5	pA/šHz
Responsivity	r		0,63		A/W
Capacitance	C_j		7	8	pF
Rise time (10-90%)	t_r		30	60	ns
Reverse voltage (bias)	V_r	5	15	20	V
Thermal drift			40	200	ppm/°C
Maximum ratings					
Reverse voltage	$V_{R\text{-max}}$			30	V
Operating temperature	T_{oper}			70	°C
Storage temperature	T_{stg}			100	°C

Test conditions: Room temperature 23°C. Reverse voltage 15 V. Light-source wavelength 940 nm.
Position non-linearity and thermal drift are valid within 80% of the detector length.

Package: 4-pin ceramic package, 15,2 mm diameter, with protective window.



2L2SP

Pin configuration:		
	1	Output X1
	2	Output Y1
	3	Output X2
	4	Output Y2

Note: Outputs Y1, Y2 and X1, X2 are respectively interchangeable. The anodes Y1, Y2 must be at negative potential compared to the cathodes X1, X2.

Application information:

The inherent resolution of a PSD is very good. It is proven to be better than one part in one million. The performance of a PSD based measurement system is thus limited by its mechanical, optical and electrical components.

To get the best performance you have to consider:
- Modulated light source. Modulation makes it possible to avoid influence of other light sources.
- Stable temperature.
- Mechanical stable system.
- High optical resolution.
- High resolution in division of the sum- and difference signals.

Resolution, optical sensitivity and measurement speed are related to each other in the PSD measurement system and you have to make the proper choices and tradeoffs for your system. Further information as schematics of a recommended hook-up is obtainable from your local distributor or from SiTek Electro Optics AB.

SiTek PSD Position Measurement electronic boards:

For most position measurement applications the SiTek PM-kit offers a complete and easy-to use solution. It is a series of general purpose, high performance, low-noise electronic boards designed for SiTek PSD. You can easily build your own measurement system using our PM-kit. Further information is obtainable from your local distributor or from SiTek Electro Optics AB.

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Appendix B

High-Performance T-1¾ (5 mm) TS AlGaAs Infrared (875 nm) Lamp

Technical Data

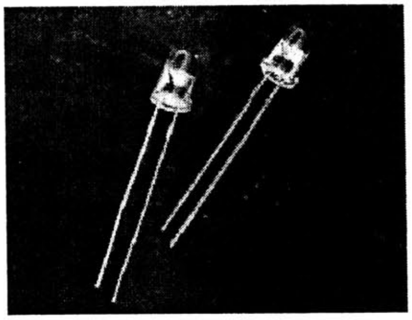
HSDL-4200 Series
HSDL-4220 30°
HSDL-4230 17°

Features

- **Very High Power TS AlGaAs Technology**
- **875 nm Wavelength**
- **T-1¾ Package**
- **Low Cost**
- **Very High Intensity:**
  HSDL-4220 - 38 mW/sr
  HSDL-4230 - 75 mW/sr
- **Choice of Viewing Angle:**
  HSDL-4220 - 30°
  HSDL-4230 - 17°
- **Low Forward Voltage for Series Operation**
- **High Speed: 40 ns Rise Times**
- **Copper Leadframe for Improved Thermal and Optical Characteristics**

Applications

- **IR Audio**
- **IR Telephones**
- **High Speed IR Communications**
  IR LANs
  IR Modems
  IR Dongles
- **Industrial IR Equipment**
- **IR Portable Instruments**

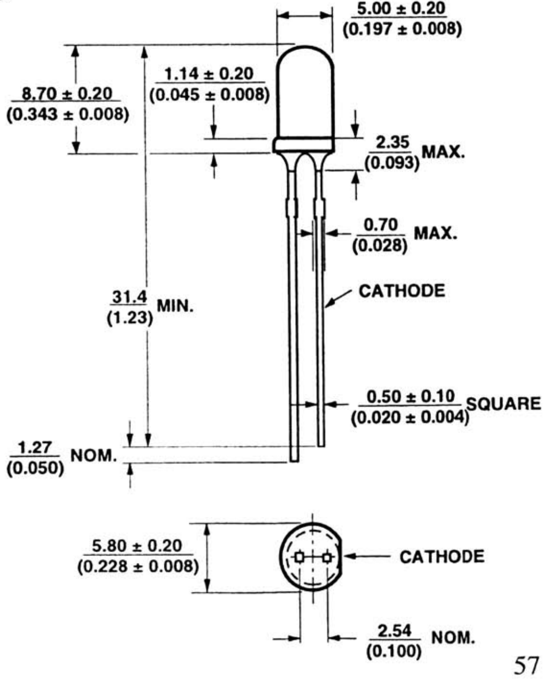


- **Interfaces with Crystal Semiconductor CS8130 Infrared Transceiver**

Description

The HSDL-4200 series of emitters are the first in a sequence of emitters that are aimed at high power, low forward voltage, and high speed. These emitters utilize the *T*ransparent *S*ubstrate, double heterojunction, *Al*uminum *Ga*llium *As*enide (TS AlGaAs) LED technology. These devices are optimized for speed and efficiency at emission wavelengths of 875 nm. This material produces high radiant efficiency over a wide range of currents up to 500 mA peak current. The HSDL-4200 series of emitters are available in a choice of viewing angles, the HSDL-4230 at 17° and the HSDL-4220 at 30°. Both lamps are packaged in clear T-1¾ (5 mm) packages.

Package Dimensions



The package design of these emitters is optimized for efficient power dissipation. Copper leadframes are used to obtain better thermal performance than the traditional steel leadframes.

The wide angle emitter, HSDL-4220, is compatible with the IrDA SIR standard and can be used with the HSDL-1000 integrated SIR transceiver.

Absolute Maximum Ratings

Parameter	Symbol	Min.	Max.	Unit	Reference
Peak Forward Current	I_{FPK}		500	mA	[2], Fig. 2b Duty Factor = 20% Pulse Width = 100 µs
Average Forward Current	I_{FAVG}		100	mA	[2]
DC Forward Current	I_{FDC}		100	mA	[1], Fig. 2a
Power Dissipation	P_{DISS}		260	mW	
Reverse Voltage (I_R = 100 µA)	V_R	5		V	
Transient Forward Current (10 µs Pulse)	I_{FTR}		1.0	A	[3]
Operating Temperature	T_O	0	70	°C	
Storage Temperature	T_S	-20	85	°C	
LED Junction Temperature	T_J		110	°C	
Lead Soldering Temperature [1.6 mm (0.063 in.) from body]			260 for 5 seconds	°C	

Notes:

1. Derate linearly as shown in Figure 4.
2. Any pulsed operation cannot exceed the Absolute Max Peak Forward Current as specified in Figure 5.
3. The transient peak current is the maximum non-recurring peak current the device can withstand without damaging the LED die and the wire bonds.

Electrical Characteristics at 25°C

Parameter	Symbol	Min.	Typ.	Max.	Unit	Condition	Reference
Forward Voltage	V_F	1.30	1.50 2.15	1.70	V	I_{FDC} = 50 mA I_{FPK} = 250 mA	Fig. 2a Fig. 2b
Forward Voltage Temperature Coefficient	$\Delta V/\Delta T$		-2.1 -2.1		mV/°C	I_{FDC} = 50 mA I_{FDC} = 100 mA	Fig. 2c
Series Resistance	R_S		2.8		ohms	I_{FDC} = 100 mA	
Diode Capacitance	C_O		40		pF	0 V, 1 MHz	
Reverse Voltage	V_R	2	20		V	I_R = 100 µA	
Thermal Resistance, Junction to Pin	$R\theta_{jp}$		110		°C/W		

Optical Characteristics at 25°C

Parameter	Symbol	Min.	Typ.	Max.	Unit	Condition	Reference
Radiant Optical Power HSDL-4220	P_O		19 38		mW	I_{FDC} = 50 mA I_{FDC} = 100 mA	
HSDL-4230	P_O		16 32		mW	I_{FDC} = 50 mA I_{FDC} = 100 mA	
Radiant On-Axis Intensity HSDL-4220	I_E	22	38 76 190	60	mW/sr	I_{FDC} = 50 mA I_{FDC} = 100 mA I_{FPK} = 250 mA	Fig. 3a Fig. 3b
HSDL-4230	I_E	39	75 150 375	131	mW/sr	I_{FDC} = 50 mA I_{FDC} = 100 mA I_{FPK} = 250 mA	Fig. 3a Fig. 3b
Radiant On-Axis Intensity Temperature Coefficient	$\Delta I_E/\Delta T$		-0.35 -0.35		%/°C	I_{FDC} = 50 mA I_{FDC} = 100 mA	
Viewing Angle HSDL-4220	$2\theta_{1/2}$		30		deg	I_{FDC} = 50 mA	Fig. 6
HSDL-4230	$2\theta_{1/2}$		17		deg	I_{FDC} = 50 mA	Fig. 7
Peak Wavelength	λ_{PK}	860	875	895	nm	I_{FDC} = 50 mA	Fig. 1
Peak Wavelength Temperature Coefficient	$\Delta\lambda/\Delta T$		0.25		nm/°C	I_{FDC} = 50 mA	
Spectral Width-at FWHM	$\Delta\lambda$		37		nm	I_{FDC} = 50 mA	Fig. 1
Optical Rise and Fall Times, 10%-90%	t_r/t_f		40		ns	I_{FDC} = 50 mA	
Bandwidth	f_c		9		MHz	I_F = 50 mA ± 10 mA	Fig. 8

Ordering Information

Part Number	Lead Form	Shipping Option
HSDL-4220	Straight	Bulk
HSDL-4230	Straight	Bulk

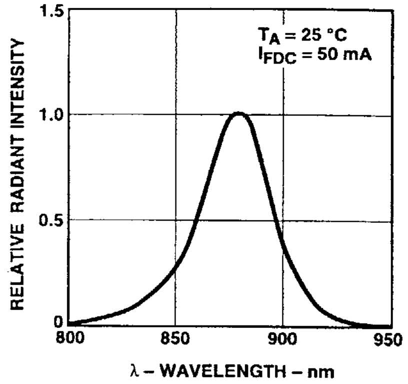


Figure 1. Relative Radiant Intensity vs. Wavelength.

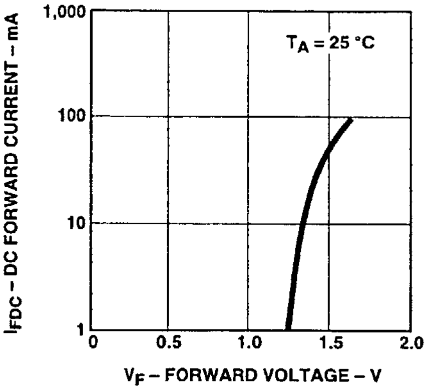


Figure 2a. DC Forward Current vs. Forward Voltage.

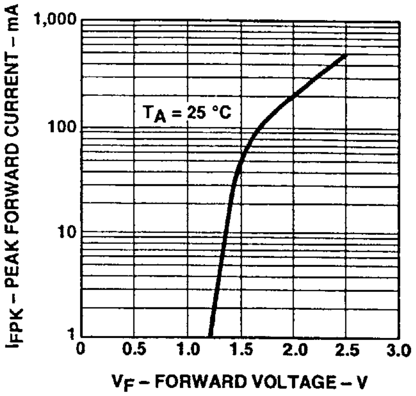


Figure 2b. Peak Forward Current vs. Forward Voltage.

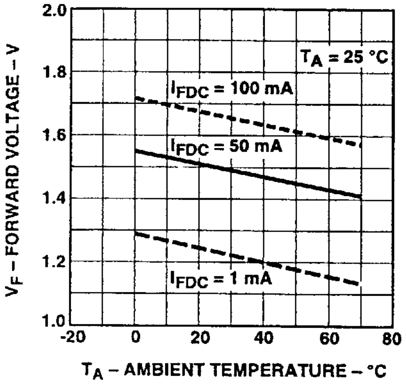


Figure 2c. Forward Voltage vs Ambient Temperature.

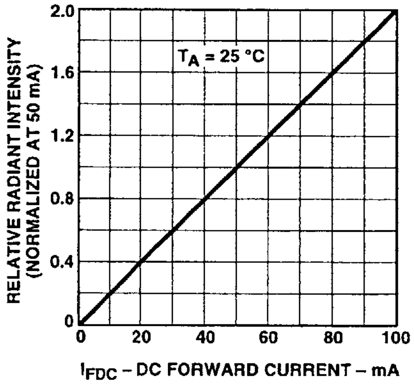


Figure 3a. Relative Radiant Intensity vs. DC Forward Current.

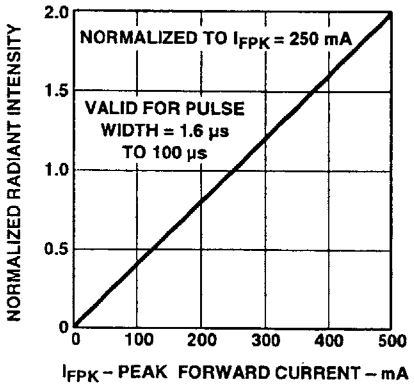


Figure 3b. Normalized Radiant Intensity vs. Peak Forward Current.

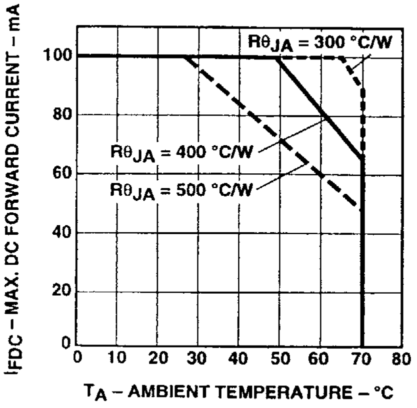


Figure 4. Maximum DC Forward Current vs. Ambient Temperature. Derated Based on T_{JMAX} = 110°C.

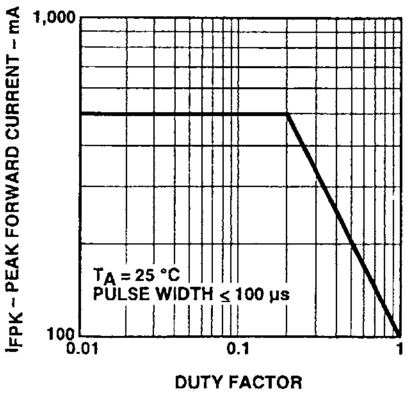


Figure 5. Maximum Peak Forward Current vs. Duty Factor.

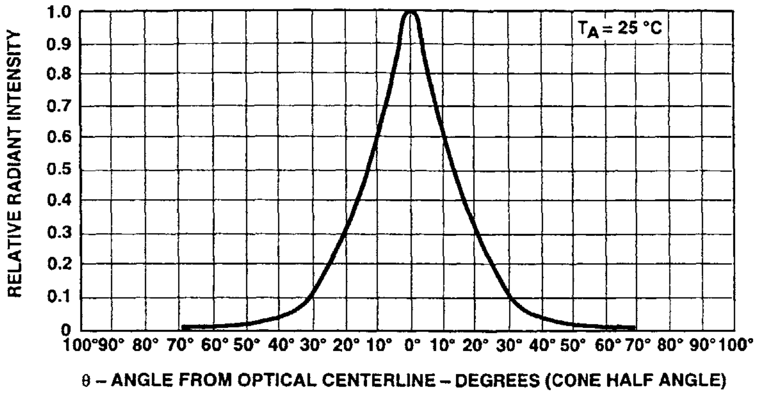


Figure 6. Relative Radiant Intensity vs. Angular Displacement HSDL-4220.

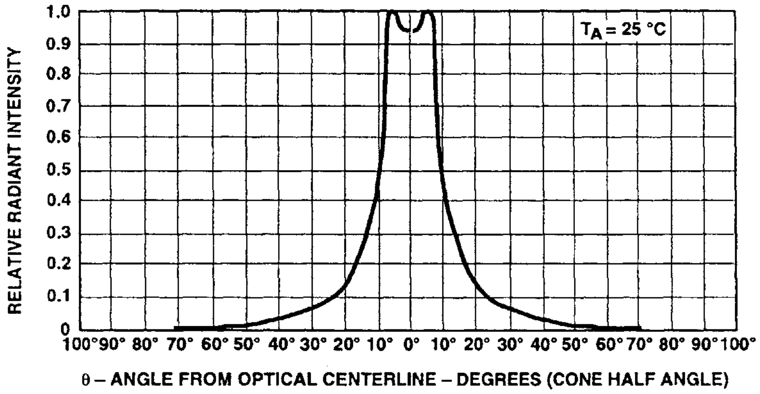


Figure 7. Relative Radiant Intensity vs. Angular Displacement HSDL-4230.

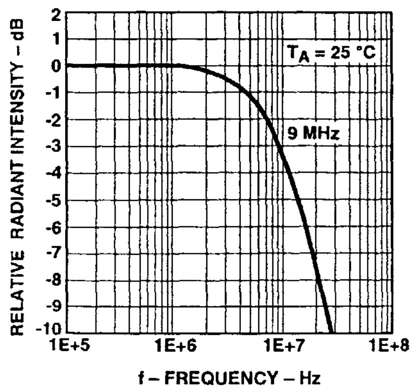


Figure 8. Relative Radiant Intensity vs. Frequency.

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Data subject to change.

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