Design of a Novel Six-Axis Metrology System for Meso-Scale Nanopositioners

by

Ryan N. King

Submitted to the Department of Mechanical Engineering
in Partial Fulfillment of the Requirements for the Degree of
Bachelor of Science in Mechanical Engineering

at the

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ABSTRACT

The purpose of this research is to develop the best possible means and methods of building a six-axis metrology system given cost and space constraints. Six axis measurements are a crucial part of precision engineering and characterizing machine performance, however commercially available sensors are not cost-efficient and are difficult to incorporate into meso-scale machines. The novel approach presented here uses three pairs of laser diodes and quadrant photodiodes to achieve six axis measurements. This paper presents a general parametric model that can predict the output of the photodiodes due to translations and rotations of the target for any geometry of the system. The device has performance characteristics of translational resolution in the range of microns depending on the geometry of the system, a bandwidth of 17.5 MHz, and dominant noise in the sensor of ±1.6 nm. This device will be useful in a variety of applications including nanomanufacturing, bioinstrumentation, Dip Pen Nanolithography, AFM, and many more.

Thesis Supervisor: Martin L. Culpepper
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CHAPTER 1

INTRODUCTION

The purpose of this research was to develop the best possible means and methods of building a six-axis metrology system given strict cost and space constraints. Six axis measurements are a crucial part of precision engineering and characterizing machine performance, but commercially available sensors are not cost-efficient or easy to incorporate into meso-scale machines. The novel approach presented here will address the need for a compact and low-cost six-axis sensor and will show how to analyze the device for different applications requiring tradeoffs in resolution, size, and range. This device will be useful in a variety of applications including nanomanufacturing, bioinstrumentation, Dip Pen Nanolithography, AFM, and many more.

The final version of the sensor uses three sets of laser diodes and quadrant photodiodes. Each quadrant photodiode captures two degrees of freedom of the motions of lasers reflecting off the target surface. This paper presents a parametric model that relates outputs of the three photodiodes to the translations and rotations of the target that is being measured.

Figure 1.1: Solid model of the final design.
1.1 Background

Many six-axis metrology systems have already been developed for precision engineering applications, however they all require sacrifices in cost, resolution, or sensor placement. It is worth noting some of the advantages and disadvantages of existing systems before delving into the design of a new sensor.

One common approach to precision instrumentation is a laser interferometer. Originally pioneered by American physicist Albert Michelson in a famous experiment that disproved the notion that light waves traveled in a light-carrying ether, interferometers provide accurate measurements by interfering two beams of light and examining changes in their interference pattern. By reflecting a measurement beam off of a reflecting surface on the target, the relative phase of the measurement beam and a static reference beam changes. Changes in relative phase of the two beams manifests itself in constructive or destructive interference that can be detected by changes in the fringe pattern of the recombined beam. Figure 1.1 shows a diagram of a Michelson interferometer.

![Image of Michelson interferometer]

**Figure 1.2: Traditional Michelson Interferometer [1].**

Today, heterodyne interferometers are most common, and they use a stabilized HeNe laser source emitting two frequency shifted and orthogonally polarized beams with known and stable frequencies. Having the beams orthogonally polarized allows them to be separated when passed through a polarized beam splitter. The PBS reflects beams of one polarization state, while passing through beams of the orthogonal polarization. The two different beams from the HeNe
The reference beam is directed toward a stationary mirror or retroreflector while the measurement beam is directed toward a mirror or retroreflector on the stage or device being measured. By passing the measurement or reference beams through a quarter wave plate twice their polarization states can be altered by 90° so that the PBS reflects them differently. Figure 1.2 shows a schematic of a basic heterodyne interferometer that takes advantage of a quarter wave plate to change the polarization state of the measurement beam so that it recombines with the reference beam on its second encounter with the PBS. The recombined beam is carried via fiber optics to a receiver which converts the combined beat frequency into a square wave and sends the signal to a variety of signal processing electronics to determine the displacement relative to the original position.

Figure 1.3: Heterodyne interferometer setup showing the various components [2].

The actual displacement measurement is taken by observing changes in the recombined beam. As the location of the target reflecting surface changes, the total path length of the measurement beam changes. This results in a change in the relative phase of the reference and measurement beams. The constructive or destructive interference caused by the superposition of the two
beams can be observed in the fringe patterns created by the recombined beams. A full cycle between two successive dark bands corresponds to a change in optical path length of the measurement beam of one wavelength, $\lambda$. The measurement beam travels to and from the target mirror, thereby effectively doubling the displacement of the target mirror. Consequently, the most basic interferometer has a linear resolution of $\lambda/2$, which is about 0.32 $\mu$m for the most common HeNe lasers operating at about 650 nm. Improvements in resolution can be achieved through multiple passes that increase the optical path length and amplify the displacement of the target mirror, through interpolation of the fringe patterns, and through use of the beat frequency generated by recombining beams with different frequencies.

The primary source of error in interferometers comes from changes in the relative phase difference between the reference beam and measurement beam. Because the measurement beam travels a different, and often longer, path than the reference beam, thermally induced growth can change the relative phase shift of the two beams. A common solution is to try to keep the measurement and reference paths collinear and similar in length so that thermal growth affects both beams equally and does not induce relative differences.

Commercially available interferometer systems are sold as modular systems where customers select laser heads, interferometers, mirrors, PBS, quarter wave plates, receivers, fiber optics, and signal processing equipment to achieve their instrumentation needs. While one laser head provides sufficient power, a unique interferometer and receiver is needed for each measurement axis. This results in interferometer setups requiring many expensive components, particularly in systems that will measure multiple axes. Additionally, because laser beam stability is important to the measurement, interferometers require high powered precisions laser, with carefully controlled environments for optimal resolution. Finally, the size of the many mirrors, retroreflectors, and receivers makes them difficult to install in small structures.

Another common metrology tool is a Coordinate Measuring Machine, or CMM. A CMM works by using a touch probe mounted on a structure that can move in three orthogonal directions. This allows the machine to locate points on a part in 3-dimension space to determine size, position, or displacement. They come in a range of sizes appropriate for taking benchtop measurements to
verifying large industrial stamped metal parts. Generally, there is a granite tabletop with guide rails on two sides to allow a bridge to travel the length of the table. The probe is mounted on a vertical structure that can move along the length of the bridge as well as vertically, allowing the probe tip to move in three orthogonal directions. Air bearings enable friction-free travel along the rail surfaces. The probe tip is a contact device that sends position data to the computer upon contact with a surface. Newer generations of CMM device may also make use of optical probes that use CCD sensors to measure edges or a dragging technique that records points at regular intervals on a surface and creates a 3D image through point-cloud data.

CMM's are a convenient and versatile tool, but are better suited for characterizing fabricated parts to compare their real dimensions to theoretical designs. The large structure of the actual machine, as well as the requirement to physically touch the target part limit their use in precision machine design. Additionally, CMM's are poorly suited to taking dynamic measurements of a moving stage because they rely on discrete data points achieved through intermittent physical contact. Finally, CMM's generally are bigger than the part being measured and would not be easily integrated into a machine's structure without significant alterations.

Finally, capacitance probes also offer a versatile means of taking data measurements along a single axis, and can be arranged to take 6-axis measurements. Capacitance probes work by measuring the capacitance between the sensor surface and the surface of the part being measured. This allows for a distance measurement without having to touch or mount a mirror on the surface of the part being measured. Circuit design and material selection are important elements to the system's resolution because the distance measurement is coming from a capacitance value. Capacitance between the sensor and the target surface is given by the equation \( C = \frac{\varepsilon A}{d} \), where \( \varepsilon \) is the dielectric constant of the medium between the plates. For precise measurements in mediums other than a vacuum, the dielectric constant will be affected by temperature, pressure, humidity, and medium type. Additionally, large probe surface areas relative to gap distance will improve the accuracy and resolution of the cap sensory by decreasing edge effects of electromagnetic waves and providing an averaging effect on surface
finish topology. A multi-axis metrology system requires placing cap probes in non-redundant positions with one probe per axis measured.

Cap probes offer reasonable resolution in a simple and cost effective package that could more easily be incorporated into a machine structure than an interferometer, but are not without drawbacks. A capacitance measurement is a function of the distance between the probe and target surface, so the probes must be placed close to their target for optimal resolution. This close physical proximity limits their range and also imposes strict requirements on where they must be placed in a machine to make functional measurements. Finally, the capacitance reading is subject to material and electronic shielding considerations that reduce their functionality in certain situations.

<table>
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<td>Resolution (nm)</td>
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<td>-----------------</td>
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<tr>
<td>Interferometer</td>
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<tr>
<td>CMM</td>
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<tr>
<td>Cap Probes</td>
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2.1 Design Requirements

The design requirements for the six-axis sensor follow from the weaknesses of the previously mentioned existing six-axis sensors. In general, existing systems offer sufficient resolution but their price or size is prohibitive. Consequently, the requirements for this design focused on keeping the overall package small and inexpensive. One potential application for the sensor was to incorporate it into the HexFlex nanomanipulator developed at MIT’s Precision Compliant Lab. This device is “hockey puck” sized and would need to accommodate the sensor without substantial modifications. Another concern, cost, would be addressed by reducing the number of components and using low fidelity instruments when possible. Desired resolution for the system was on the order of 10, however size and cost were prioritized over resolution. PCSL has a plethora of high resolution metrology options, and the focus of this research was on addressing the need for compact and inexpensive sensors.

Table 2.1: Sensor functional requirements.

<table>
<thead>
<tr>
<th>Degrees of Freedom Captured</th>
<th>Resolution</th>
<th>Accuracy</th>
<th>Repeatability</th>
<th>Cost</th>
<th>Size</th>
</tr>
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<tbody>
<tr>
<td>6</td>
<td>10nm</td>
<td>10nm</td>
<td>1nm</td>
<td>&lt;$1000</td>
<td>10cm x 10cm x 10cm</td>
</tr>
</tbody>
</table>

2.2 Design Process

The first approach considered for this device was modifying a six-axis interferometer to meet the functional requirements and constraints of the project. Several six-axis interferometer designs exist that offer excellent resolution in both translational and rotational displacements.
One design put forth by Zhan and Menq [3] combines two separate interferometer systems, one with a retroreflector and one with a plane mirror reflector, to create a six axis sensor. Their prototype achieves resolution of 1.24 nm in translation and tens of nanoradians in rotation with a range of $5 \times 5 \times 5$ mm$^3$ in translation and $8^\circ \times 8^\circ \times 8^\circ$. Figure 2.1 shows the layout of their modified Michelson interferometer.

![Figure 2.1: Modified Michelson interferometer by Zhan and Menq.](image)
To compare to another multi-axis interferometer system, Kuang, Hong, and Jun-Ni [4] also put forth a design for a five-axis laser interferometer system that was intended to be simpler and more compact and than existing interferometers and also capable of operating in more demanding environments than carefully controlled labs. Their system is capable of accuracies of +/- 0.2 µm in translation and +/- 0.15 arc seconds in rotation. It also accomplishes the five-axis measurement by mounting two objects on the reflecting target, a plane mirror and a retroreflector. The six-axis design presented by Zhan and Menq requires the placement of six different retroreflectors on the target, increasing the size and cost of their device in comparison the simpler 5 axis design. The design presented by Kuang, Hon, and Jun-NI still involves nearly 30 components in addition to the electronics to process the signal. Figure 2.3 shows the layout of their five-axis interferometer.
The size, complexity, and cost of multi-axis laser interferometer systems make them ill-suited to meet the design parameters presented earlier. An alternative approach using a laser triangulation approach was explored next. In a laser triangulation system, light from a laser beam strikes the target surface and a lens focuses the scattered light onto a photodetector. The photodetector track displacement of the spot on its surface, which combined with information about the geometry of the laser, photodetector, and surface can be used to calculate displacement of the target surface. Displacement sensors using laser triangulation are commercially available from Keyence, which uses a CCD sensor to track the movement of a laser beam reflected off the target surface. These single axis displacement sensors have a maximum resolution of 0.01 μm, a range of 10 mm and bandwidth of 50 kHz. This performance comes at a price of $7-10,000 per sensor, with 6 sensors necessary for full six-axis capability.

Although commercially available laser triangulation systems are prohibitively expensive, their attributes make them ideal for PCSL's intended applications and so they serve as a starting point for the device presented herein. Laser triangulation systems have many advantages over interferometers. For example, they don't require stabilized two frequency laser like the HeNe laser head often used in interferometers, and can instead make use of compact and low power
laser diodes. Additionally, using photodiodes as sensors drastically reduces the complexity of
the detection and signal processing components of an interferometer. Photodiodes output a
signal directly proportional to the displacement of the reflected laser spot, making it very easy to
determine the beam displacement. This also leaves the amplification of the displacement to the
opto-mechanical layout of the system. This reduces the overall size of the system by allowing
the use of small mirrors and angular amplification techniques instead of large and complicated
electronics.

A small, two-axis sensing device was created by Latt et al [5], and showed that a position
sensitive photodiode (PSD) and a laser diode could be used to track in plane translations. This
system was similar to the laser triangulation systems offered by Keyence in that it uses a sensor
that tracks displacement of an incident laser beam to calculate motion of the target, however Latt
et al mounted the laser directly onto the target of interest rather than reflecting the beam off a
surface on the target. Latt et al showed that by using a PSD with a 10 mm² sensing area and a 7
mW laser diode they could track translational displacements in the plane of the sensor with a
maximum resolution of 0.3 µm at the center of the PSD and 7 µm at the edges. Figure 2.4 shows
their experimental setup.

Figure 2.4: Two-axis sensor by Latt, et al.
Given that the pairing of one laser and one PSD has been shown to give measurements in two axes, it can be shown that three of these pairs can be combined to create a six-axis sensor. This can be proved by generalizing from Maxwell’s principles of constraint expressed as:

\[ R = 6 - C \]  

(1.1)

Where \( R \) is the number of degrees of freedom and \( C \) is the number of non-redundant constraints. In the same way that a system with 3 non-redundant constraints will have 3 degrees of freedom, a system with 3 non-redundant single axis sensors will be able to measure 3 degrees of freedom. Consequently, using three pairs of lasers and PSD’s arranged so that they give non-redundant readings will form a six-axis sensing system.

The design presented by Latt et al cannot be scaled up easily because it is not feasible to mount three laser diodes on each target that is measured. Rather, the ideal sensor would combine the remote sensing and beam reflecting approach embodied by laser triangulation systems with Latt et al’s pairing of a PSD and laser diode scaled up to six axes.

The six-axis sensor presented here uses mirrors mounted on the target with three laser beams aligned so that they shine on the mirrors and are reflected onto the surface of a quadrant photodiode. There is no need for a focusing lens in front of the photodiode or a large structure to house the components like the Keyence design because the reflected laser beam is perpendicular to the photodiode surface. Separating the lasers from the photodiode makes them easier to incorporate into an existing machine structure, and allows the laser to be moved independently of the photodiode for alignment purposes. There are no requirements on the proximity of the sensors to the target as in cap probes, and in fact increasing the distance between the two improves rotational resolution. By using quadrant photodiodes, two inplane translations can be measured on each photodiode. Quadrant photodiodes are used instead of PSD’s because they give a more uniform response over their surface, they require no external power, and can fit into smaller spaces because they have no PCB board attached. Proper arrangement of the lasers, mirror surfaces on the target stage, and the photodiodes gives six unique displacements that, given the geometry of the system, can be used to find the six-axis displacement.
2.3 Components

The quadrant photodiodes are model QP5.8-6-TO5 made by Pacific Silicon Sensor [6]. They have four 1.2 mm$^2$ sensors with 50 µm gaps between sensors. The four elements are fabricated on a single chip, but their smaller size increases uniformity and performance matching. The photodiode acts as a photovoltaic in that each quadrant outputs a current proportional to the intensity of the light hitting it. The photodiode responsivity peaks at 0.64 A/W at around 900 nm, and is 0.40 at 633 nm which corresponds to a typical red light laser.

![Diagram of the Pacific Silicon Sensor quadrant photodiode.](image)

**Figure 2.5:** Diagram of the Pacific Silicon Sensor quadrant photodiode.

![Spectral response of the quadrant photodiode.](image)

**Figure 2.6:** Spectral response of the quadrant photodiode.
The lasers used are adjustable focus 650 nm 5 mW from U.S. Lasers Inc, part number M65051 [7]. Adjustable focus lasers allow for a variety of system geometries in different applications simply by refocusing the laser on the photodiode surface.

Figure 2.7: 5mW adjustable focus laser.
3.1 Experimental Setup

To test this approach, a simple two-axis proof of concept prototype was developed with a laser mounted on an optical micrometer stage and pointed normal to the photodiode surface. By using the micrometer stage to actuate the laser, a rough calibration of the sensor output and circuitry could be made.

A vertical and horizontal displacement of the laser spot on the photodiode surface may be found by converting the currents produced by each quadrant in the photodiode and comparing changes in the output voltages of each quadrant. For a photodiode aligned so that gaps dividing each quadrant are horizontal and vertical, and numbering the quadrants 1 – 4 starting with the upper left quadrant and continuing clockwise the voltage outputs representing the X and Y directions are:

\[
V_x = \frac{(V_2 + V_3) - (V_1 + V_4)}{V_1 + V_2 + V_3 + V_4}
\]

\[
V_y = \frac{(V_1 + V_2) - (V_3 + V_4)}{V_1 + V_2 + V_3 + V_4}
\]

The output level of the laser diode fluctuates and different amounts of light hits the inactive gap between sensors, so the voltages are normalized by dividing them by the total amount of incident light. As the spot travels along the surface of the photodiode, changes in voltage output from a reference point will become apparent.
Each quadrant outputs a current proportional to the light hitting it, with a conversion factor of 0.45 A/W. In order to take readings in dSpace, the inputs must be voltages so the current is run across a resistor to ground and the voltage drop is conveyed to dSpace as the output from each quadrant. The laser is rated at 5 mW which results in 2.25 mA total output from the entire photodiode. The current is run across a 2 kΩ resistor so that the total output is 4.5 volts, which falls into dSpace's input range of 1-10 V. The laser is powered by a +3V output and ground connection from the power supply.

3.2 Data Processing

Once the voltages are received by dSpace, they are normalized to the total output of the laser to account for fluctuations in the laser power and ambient light and converted into voltage changes that correlate to displacements in relevant directions. These steps can be done simultaneously for all quadrants using matrices that input data from each quadrant and output an X and Y voltage that has been normalized to the total photodiode output. Figure 3.2 shows a simulink
layout that takes in 4 voltage signals from each quadrant, amplifies them by a gain of 100, outputs each voltage to a graph, muxes the voltages together into one vector, converts quadrant voltage signals into directional voltage signals (top, bottom, left, right), normalizes the signals by dividing by the total voltage, and finally outputs voltages signals in the x and y directions.

Figure 3.2: Layout of data processing program in Simulink.

Where the operations $C$ and $D$ on the input vector $u$ are as follows:

$$u = \begin{bmatrix} V_1 \\ V_2 \\ V_3 \\ V_4 \end{bmatrix}$$

$$C = \begin{bmatrix} 1 & 1 & 0 & 0 \\ 0 & 1 & 1 & 0 \\ 0 & 0 & 1 & 1 \\ 1 & 0 & 0 & 1 \\ 1 & 1 & 1 & 1 \end{bmatrix}$$

$$D = \begin{bmatrix} 0 & 1 & 0 & -1 \\ 1 & 0 & -1 & 0 \end{bmatrix}$$
\[
D \cdot u_i = \begin{bmatrix} x \\ y \end{bmatrix} = \begin{bmatrix} \frac{(V_2 + V_3)}{(V_1 + V_2 + V_3 + V_4)} - \frac{(V_1 + V_4)}{(V_3 - V_4)} \\ \frac{V_1 + V_2 + V_3 + V_4}{(V_1 + V_2)} - \frac{(V_1 + V_2 + V_3 + V_4)}{(V_3 - V_4)} \end{bmatrix}
\] (3.2)

### 3.3 Results

With the laser mounted on a micrometer stage, it was possible to manually actuate the laser and take data to calibrate the system. Specifically, the noise limitations of the analog to digital converter and dSpace needed to be characterized and a correlation between voltage changes and displacement needed to be determined. In this experiment, the sensor was mounted at 45° from vertical and various laser spot sizes were used. Focusing the laser beam tightly on the center of the photodiode created a well defined spot will relatively large power density, however the overall range of the system was limited. The range is limited to the extent that the laser spot must still cover part of all quadrants because the displacement reading relies on changes in relative outputs of each quadrant. Once it leaves one of the quadrants, it is impossible to tell relative changes. At the extreme, if the spot was concentrated entirely in one quadrant, it would be impossible to tell if the spot moves within the quadrant because the sensing system relies on relative changes between the output of all the quadrants.

The adjustable focus laser allows users to create either a tightly focused spot or a more diffuse line that can be several centimeters long depending on distance to the target. In this calibration experiment, the laser was tuned to be a line so that it could be used over a longer range and therefore check consistency across the surface of the photodiode. Figure 3.3 and 3.4 show the resulting X and Y data from a sweep covering 30 thousandths of an inch of the surface. The laser was actuated by hand and the data was sampled at 1 kHz and amplified by a 10X gain above the normal 10x gain required to compensate for the DAC board. This experiment verified the approach of using quadrant photodiodes and simple laser diodes, and showed that changes in voltages corresponding to x and y motions could be determined. In this simple example, without filtering or any attempts to improve the signal or system resolution, the system could resolve 125
microns per volt. The resolution was limited by the noise from the DAC board of \( \pm 50 \) mV, so the system resolution was 6.25 \( \mu \)m.

Figure 3.3: Voltage data along the \( X \)-axis of the photodiode.
One notable result in the Y axis data is the small change in voltage at the step around $2 \times 10^4$ samples and then abrupt jump from about -1 V to 0.5 V in the next step. This shows the nontrivial impact of the gaps between quadrants. The gap between quadrants is 50 $\mu$m wide and in this experiment the spot line was closely aligned with the y axis. The results show that as the beam moved into the gap there was an apparent reduction in voltage change as the part of the beam that would have entered a new quadrant was instead hitting a large portion of the gap. In the next step, as the beam moved out of the gap, a disproportionately large amount of light appeared to be entering the new quadrant, making for a large jump in voltage. This shows that for the most consistent results, one would want a consistent amount of light to be hitting the gap between the quadrants. This could be achieved by making the ratio of the gap area to the area of the quadrants cover by the laser spot as small as possible. One would also want a large laser spot to minimize nonlinearities introduced by the curvature of the edge of the beam spot.
4.1 General Approach

After showing that a simple adjustable focus laser diode and the quadrant photodiode could be used to take two axis measurements, design of the six-axis system began. As shown earlier, three pairs of one laser and one photodiode produced two different pieces of data on the target's motion, meaning that with the correct arrangement, a six-axis sensor could be built. The approach I chose was to detect translations in the same way that they were on the two-axis prototype. Rotations would be detected through Abbe errors that would manifest themselves as displacements of the laser spot on the photodiodes. Distinguishing between translations and rotations would be accomplished by the positioning of the lasers and sensors such that motion in each degree of freedom caused a unique change in the location of the 3 laser spots on the photodiodes.

The simplest application of this approach would have the three lasers mounted on the part to be measured but in such a way that the lasers were not collinear. For the intended uses of the sensor in small devices, such as the HexFlex and DPN machine, mounting the lasers directly onto the target was not feasible because of size and mass constraints. This called for a noncontact metrology system that would isolate the precision devices from the heat generated by the lasers. Using a similar approach to commercially available laser triangulation device, six-axis sensing could be achieved by reflecting the laser off a surface on the target to a remotely located photodiode sensor.
This arrangement has several innate advantages and disadvantages. First, since rotations are calculated through Abbe errors, the system's resolving power for rotations is merely a function of the optical path length and can be increased by placing the photodiode at a greater distance from the target. Second, the laser must reflect off the target surface at an angle normal to the surface of the photodiode. The incident and reflect laser beams cannot be collinear because of the physical constraints of the laser and sensor housing, so the incident laser beam must not be perpendicular to the mirrored surface on the target. This contact angle has a critical impact on system performance. The angle of reflection will distort the incoming laser spot shape and size and is important for achieving the proper spot on the photodiode. Additionally, the incident angle determines the system sensitivity to displacements in different directions. To achieve a particular incident angle while keeping the reflected beam normal to the photodiode surface requires careful positioning of the laser, photodiode, and placement of angled mirrors on the target device.

Finally, the system requires that the lasers not all reflect off the same point or surface on the target. The photodiodes report either the translation of the point where the laser beam is incident on the target in the two directions that are in the plane of the photodiode surface, or the Abbe error of a rotation that results in a displacement in that same plane. Therefore, if all three incident laser beams hit at the same point on the mirror and the target device moved in the plane of the mirror, there would be no displacement detected by the photodiodes.

To ensure that all six axes of motion are detected and to control the incident laser angle, a pyramid shaped mirror is mounted on the target device. By putting each reflecting surface on a different plane, there is a unique displacement of the laser spot on the photodiodes for each translation and rotation of the target.

### 4.2 Directional Sensitivity

The angle of incidence of the laser beam on the target mirror is a major determinant of the resolution of the final system and sensitivity to displacements in different directions. The angle of incidence is defined as the angle between the incident ray and a line normal to the reflecting
surface. Figure 4.1 shows a diagram with the angle of incidence and angle of reflection. The angle of incidence and the angle of reflection will always be the same magnitude.

![Diagram of the angle of incidence.](image)

**Figure 4.1: Diagram of the angle of incidence.**

The angle of incidence is important because it determines how a displacement of the target affects the location of the reflected beam. At the extreme, an angle of incidence of $90^\circ$ such that the incident beam is parallel with the reflecting surface would be infinitely sensitive to target displacements in the direction normal to the reflecting surface. Conversely, an angle of incidence of $0^\circ$ such that the incident beam is perpendicular to the reflecting surface would be insensitive to target displacements in the direction normal to the reflecting surface.

The system's resolution can be maximized given these characteristics and a few constraints. A priori, the reflected laser beam was constrained to be normal to the photodiode surface. This both simplifies the analysis of the displacement and avoids errors induced by distortion or refraction of the beam while passing through the glass cover of the photodiode. For simplicity in fabricating the device, I chose to make the photodiode surface vertical, which requires beams reflected off the target mirror surface to be horizontal. This constraint in effect determines the resolution of the system because of the relationship between the mirror angle and angle of incidence.
The angle of the reflecting surface, $\tau$, and angle of incidence, $\theta$, are related by the constraint $\theta + \tau = 90$.

Because the displacement is measured on the photodiode surface, normal to the incoming beam, we can calculate the displacement on the photodiode, $\delta$, as a function of the angle of incidence, $\theta$, and a displacement of the reflecting surface, $d$. The extra path length of the incoming beam due to the downward deflection of the reflecting surface is $a = \frac{d}{\cos(\theta)}$. We then find the projection of this line onto a line perpendicular to the reflected beam using the constraints on the angle of incidence and angle of the reflected surface.
\[
\alpha = 180 - 90 - \theta \\
\beta = 180 - 2\alpha - 90 \\
\beta = 2\theta - 90 
\]

The projection of the extended incoming path length onto a line perpendicular to the reflected path is then:

\[
\delta = \left( \frac{d}{\cos(\theta)} \right) \cdot (\cos(2\theta - 90)) \tag{4.1} 
\]

Where \(d\) is the displacement of the reflecting surface in a direction along its normal vector. Figure 4.4 shows the effective displacement on the surface of the photodiode as function of the angle of incidence. This shows that at an angle of incidence of 30° the magnitude of the displacement of the target mirror surface exactly equals the displacement of the beam on the photodetector. For larger angles of incidence beyond 30° the displacement of the target mirror can be amplified by up to a factor of 2, while angles of incidence below 30° reduce the apparent displacement.

Figure 4.4: Displacement amplification as a function of angle of incidence.
This gives a relationship between the displacement seen by the photodiode and a displacement of the reflecting surface in the direction of its normal vector, however it would be more convenient to characterize the displacement of the reflecting surface in terms of the global machine coordinate system. To convert between the machine coordinate system and a coordinate system on the surface of the mirror we use the following relationship:

\[
\begin{bmatrix}
X_{\text{system}} \\
Y_{\text{system}}
\end{bmatrix} = \begin{bmatrix}
\cos(\tau) & \sin(\tau) \\
-\sin(\tau) & \cos(\tau)
\end{bmatrix} \begin{bmatrix}
X_{\text{mirror}} \\
Y_{\text{mirror}}
\end{bmatrix}
\]  

(4.1)

We can then find overall system sensitivity to target displacements in the X and Y direction of the global coordinate system as a function of the angle of incidence. Because the system is only sensitive to displacements in the \(Y_{\text{mirror}}\) direction, the sensitivity in a direction on the global coordinate system is a function of the angle amplification and how closely that direction is aligned with the \(Y_{\text{mirror}}\) direction. Figure 4.5 shows the results of this model. The device has equal sensitivity in the X and Y directions when the angle of incidence is 45 degrees, and also has a 1:1 relationship between target displacement and beam displacement on the sensor at this angle. At larger angles of incidence the displacement amplification increases, but because the reflected beam is constrained to parallel, the reflecting surface must become increasingly parallel to the horizontal. This means that the sensitivity is limited to a 1:1 ratio in the machine X direction but can amplify the sensitivity to displacements in the machine Y direction by up to a factor of two. This means that the experimentally recorded resolution of the photodiodes of 6.25 \(\mu\text{m}\) can be improved to 3.13 \(\mu\text{m}\).
4.3 Parametric Modeling

The six-axis sensor takes in outputs from 4 quadrants in 3 photodiodes and needs to convert that data into 3 rotations and 3 translations. To do so, a parametric model needed to be developed that describes the changes in point of intersection of the incoming beam and the reflecting surface on the target. This point is affected by translation of the stage, as well as rotation of the stage. Additionally, the model needed to capture the effects of a rotation of the stage that changes the angle of the reflected laser beam and resulting displacement of the laser spot on the photodiode.

First, a general model was developed to find the point of intersection of a beam and a plane in 3 dimensional space. This may be modeled with a laser beam parameterized in $t$, originating from the point described by the vector $\vec{b}$, and traveling along a unit vector $\hat{p}$ such that every point

![Figure 4.5: Displacement amplification in machine coordinate system.](image-url)
along the beam can be described by some value $t$. For a plane described by its unit normal $\hat{a}$ located a distance $c$ along $\hat{a}$ from the origin, the beam crosses the surface of the plane when the dot product of the beam vector and the normal vector equals $c_a$. This is written as

$$ (\vec{b} + \hat{p}t) \cdot \hat{a} = c_a \quad (4.3) $$

The point of intersection of the beam and the plane may be found by solving for $t$:

$$ \vec{b}\hat{a} + \hat{p}t\hat{a} = c $$
$$ \hat{p}t\hat{a} = c_a - \vec{b}\hat{a} $$
$$ t\hat{p}\hat{a} = c_a - \vec{b}\hat{a} $$

$$ t_{\text{reflection}} = \frac{c_a - \vec{b}\hat{a}}{\hat{p}\hat{a}} \quad (4.4) $$

Translations of the stage relative to the origin are captured by changing the vector’s starting location, $\vec{b}$.

$$ \vec{b}_{\text{trans}} = \begin{pmatrix} 1 & 0 & 0 & \Delta_x \\ 0 & 1 & 0 & \Delta_y \\ 0 & 0 & 1 & \Delta_z \\ 0 & 0 & 0 & 1 \end{pmatrix} \cdot \vec{b} \quad (4.5) $$

Translations are calculated by changing the location of laser beams because it is easier to handle rotations of the stage separately from translations. The displacements along each axis refer to changes in the relative position of $\vec{b}$ and the stage, so if the stage moves in the negative $Z$ direction, $\Delta_z$ will be positive because the distance between the stage and $\vec{b}$ increased.

Rotations of the stage cause the reflecting surface to change position, and consequently change the point of intersection between the beam and the surface. Rotations are modeled by multiplying the surface normal $\hat{a}$ by a rotation matrix corresponding to the rotation that surface performed about the system origin. These rotation matrices are:
Translations and rotations of the stage are then taken into account when calculating the point of intersection between the laser beam and mirror surface. Because the rotations are taken about the origin, \( c_o \) stays constant. From equation 4.4, the new point of intersection as the target rotates or translates is:

\[
\mathbf{I} = b_{translation} + pt_{reflection}
\]

To model the reflection of the incoming laser beam off the target mirror surface, the incoming beam is projected onto the normal vector of the incident plane:

\[
proj = (\hat{p} \cdot \hat{a}_{rotation}) \cdot \hat{a}_{rotation}
\]
The corresponding error vector describes the difference between the incoming beam and its projection onto the surface normal. This error vector also describes the projection of the incoming laser beam onto the reflecting surface.

\[ \vec{e} = \hat{p} - \text{proj} \]  

(4.10)

The reflected vector may be found by then reversing the projection and adding the error vector to it:

\[ \hat{r} = -\text{proj} + \vec{e} \]  

(4.11)

This equation simplifies to:

\[ \hat{r} = -2(\hat{a}_{\text{rotation}} \cdot \hat{p}) \cdot \hat{a}_{\text{rotation}} + \hat{p} \]  

(4.12)

The reflected beam may then be described in the same manner as the incoming beam by defining a point on the line and its unit vector and parameterizing the vector in a new \( t \). For the reflected beam, the point of reference is the point of intersection with the reflecting plane, and the unit vector is \( \hat{r} \).

\[ \text{reflected beam} = \bar{I} + \hat{r}t \]  

(4.13)

Finally, the intersection of the reflected beam with the photodiode surface is calculated. The photodiode surface is described by the same general form presented in equation 4.3, with a surface normal unit vector, \( \hat{s} \), and with a constant, \( c_s \), that the describes the magnitude of the distance from the origin to the plane along the unit normal vector.

\[ (\bar{I} + \hat{r}t) \cdot \hat{s} = c_s \]  

(4.14)
Solving for $t_{\text{photodiode}}$ describes the point where the reflected ray intersects the photodiode. Using the solution for $t$ at the intersection of a line and a plane presented in equation 4.4:

$$t_{\text{photodiode}} = \frac{c_s - \bar{T} \cdot \hat{s}}{\hat{r} \cdot \hat{s}} \quad (4.15)$$

The location of the point on the photodiode surface as a function of the system geometry and the translational and rotational motions of the stage is then:

$$\text{PhotodiodeSpot} = \bar{b}_{\text{translation}} + \hat{p}_\text{reflection} + \hat{r}_t \text{ photodiode} \quad (4.16)$$

The error vector between two measurements of the spot location on the photodiode surface describes the translation of the laser spot on the surface of the photodiode. This vector is in terms of system geometry known a priori, like the position and angle of laser beams, reflecting surfaces, and the photodiode, and then in terms of rotations and translations of the stage.
5.1 Bandwidth

The bandwidth of a metrology system is a function of three different elements, the bandwidth of the sensors, the bandwidth of the signal processing electronics, and the bandwidth of the actual mechanical system being actuated. In this device, the bandwidth of the quadrant photodiodes can be determined from the rise time listed on the manufacturer’s data sheet. It reports the photodiode's rise time as 20 ns when using a laser at 850 nm. Although a red laser at 650 nm is used in this experiment, the following will show that the sensor's bandwidth is sufficiently greater than other components that using rise times from a slightly different laser is acceptable. For first order systems modeled with a single pole and with rise time defined as the time for a signal to transition from 10% to 90% of the maximum signal amplitude, the bandwidth is defined as:

\[ B = \frac{0.35}{t_r} \] (5.1)

Where \( B \) is the system bandwidth and \( t_r \) is the rise time from the manufacturer’s data sheet. The quadrant photodiode’s reported rise time is 20 ns, which results in a photodiode bandwidth of 17.5 MHz.

The other element of the overall system bandwidth is the sampling bandwidth. We know that the Nyquist frequency, which is half the sampling frequency, must be greater than the bandwidth of the signal being sampled. Mechanically actuated stages such as the F-206 have a total system bandwidth on the order of 1 kHz. Consequently, one would want to sample the signal at least at 2 kHz, and preferably one decade faster, at 10 kHz. This shows that the bandwidth of the
photodiode is approximately three orders of magnitude faster than the necessary sampling frequency to adequately capture the actuator motions. As such the system bandwidth is more than capable of capture mechanically actuated motions and is limited by the speed of the signal processing and data acquisition system rather than the bandwidth of the photodiode.

5.2 Noise

Random noise in the integrated metrology system comes from three main sources, thermal noise, shot noise, and flicker noise. Thermal noise comes from dissipative processes coupled to thermal reservoirs, such as a resistor. Resistors, even when carrying no current, have a fluctuating voltage across their terminals. This thermal noise in resistors is called Johnson noise and can be modeled as a noise voltage source in series with an ideal (noiseless) resistor. Senturia presents an approach to modeling noise based on noise power and the spectral density function of a noise source [8]. The spectral density function describes the total mean-square noise of a broadband noise source over its frequency range. Integrating the spectral density function, $S_n$, over the frequency range gives the total mean square noise:

$$\overline{v_n^2} = \int_0^\infty S_n(f)df$$

(5.2)

If we then run the input signal through a low pass filter to filter out noise outside the bandwidth of our mechanically actuated system we can show that the mean-square output of the noise in the filtered signal is a function of the resulting frequency range.

$$\overline{v_o^2(f_o, \delta f)} = S_n(f_o)\delta f$$

(5.3)

Where $\delta f$ is the range of frequencies, or in this case the bandwidth of the filtered signal, centered around $f_o$.

In the case of Johnson noise, the spectral density function of a voltage noise source in a resistor is defined as:
\[ S_n(f) = 4k_BTR \]  

(5.4)

Where \( k_B \) is Boltzmann's constant, \( T \) is the temperature of the resistor in Kelvin, and \( R \) is the value of the resistance in ohms. We can then define the Johnson mean-square noise of a signal passed through a low pass filter with unity gain over a bandwidth of \( \Delta f \) as:

\[ \overline{v_n^2} = 4k_BTR\Delta f \]  

(5.5)

Where

\[ k_B = 1.381 \times 10^{-23} \text{ J} \cdot \text{K}^{-1} \]
\[ T = 300 \text{ K} \]
\[ R = 2k\Omega \]
\[ \Delta f = 10\text{kHz} \]

This results in rms Johnson noise of \( 1.443 \times 10^{-6} \text{ V} \).

Shot noise is caused by the random arrival of discrete energy carriers, such as electrons in an electronic current or photons in an optical system. The magnitude of a signal increases faster than the magnitude of shot noise, so the influence of shot noise is inversely proportional to signal strength. Shot noise can be modeled using the same spectral noise approach as in Johnson noise, with a spectral noise function for DC current of:

\[ S_n = 2q_eI_{DC} \]  

(5.6)

Where \( q_e \) is the charge of an electron equal to \( 1.602 \times 10^{-19} \text{ C} \) and \( I \) is the current output by the quadrant photodiode. The maximum current put out by the photodiode would occur when the entire laser spot is incident on one quadrant of the photodiode and none of the beam is hitting the gap between quadrants. In this case \( I_{DC} = 2mA \). We then define the shot mean-square noise of the filtered signal as

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\[ v_n^2 = 2q_e I_{DC} \Delta f \]  \hspace{1cm} (5.7)

This results in rms shot noise of $6.346 \times 10^{-9} \, A$ or $1.269 \times 10^{-5} \, V$.

It is useful to note that the shot noise will generally be one quarter of this value as the incident light will be roughly split evenly amongst the quadrants. While the maximum shot noise occurs when the beam is concentrated on one quadrant, the signal to noise ratio is actually at its best in this case.

The noise caused by the DAC is significantly greater than the Johnson noise or shot noise in the actual photodiode circuits. When taking the data for the two-axis prototype, the DAC converter noise was $\pm 50$ mV, which is three orders of magnitude higher than the noise calculated using the spectral noise function model.
6.1 Overview

This paper has presented the design and prototype testing for a novel six-axis sensor. Six-axis measurements are a crucial part of precision engineering and machine design, however commercially available systems are not cost-efficient and are difficult to incorporate into mesoscale machines. The sensor presented herein has many advantages over existing products in terms of cost, size, and flexibility. A two-axis prototype was developed that showed how one laser and photodiode pair could be set up to give measure two displacements in the plane of the sensor. This idea was extrapolated to a six-axis sensor by arranging three of these pairs around a mirror mounted on the target to be measured. The system’s sensitivity to translational motion was shown to be a function of the angle of incidence of the laser beam, and a function describing the tradeoffs in sensitivity in each direction as a function of the system geometry was developed. A comprehensive parametric model was also developed to show how rotations and translations of the target stage manifest themselves in changes in the location of the laser beam spots on the photodiode surfaces. The parametric model can applied to nearly any setup by simply inputting the geometry of the locations and angles of lasers and mirrors. This allows for a flexible system that can be installed in a range of devices. Finally, the noise and bandwidth of the system was characterized. The response time of the photodides gives the system a bandwidth of 17.5 Mhz, which is more than sufficient for the actuator bandwidth and desired sampling frequency. The noise was shown to be almost entirely from the DAC board, which created noise of about ± 50 mV.
6.2 Unique Contributions

This paper identified an unsatisfied market for six-axis sensors and developed a new application of laser diodes and photodiodes to meet that need. A two-axis prototype was developed as a proof-of-concept, and the electronics and signal processing to get meaningful position data from the photodiode outputs were presented. A design for six-axis implementation of this approach was developed using tiny mirrors mounted on the target device. Constraints on the system geometry, such as the unique location of the reflecting mirrors and relationship between angle of incidence and mirror angle were also identified. A model was presented that showed how the geometry of the lasers and mirrors could be used to amplify the target displacement. Additionally, a general model was developed that could calculate the photodiode outputs as functions of device translations and rotations for any system geometry. The mathematical procedures for accounting for translations and rotations were developed using linear algebra and rotation matrices. Finally, designs for future testing on an F-206 hexapod nanopositioner and the HexFlex nanopositioner were presented.

6.3 Future Work

Two experimental setups were envisioned to test the six-axis sensor and its model in the future. One setup made use of the lab’s Physik Instrument F-206 hexapod nanopositioner. The F-206 has a six-axis motion stage with three stationary platforms positioned around the stage. A pyramid shaped mirror could be mounted on the nanopositioner stage and lasers and photodiodes would be mounted on the stationary platforms. This design allows for testing of a range of mirror and laser angles because of the flexibility in mounting locations and access to parts.
Figure 6.1: Solid model of experimental setup on hexapod nanopositioner.

Figure 6.2: Part drawing for short laser mounts.
Figure 6.3: Part drawing for tall laser mount.

Figure 6.4: Part drawing for mirror mounted on target device.
The pyramid shaped mirror would have three surfaces with a thin layer of polished silicon wafer glued onto the surface to act as a mirror. Two of the reflecting surfaces are angled at 20° while the other is at 60°. It was designed this way to verify the previously shown model for machine sensitivity as well as to accommodate the structure of the F-206. The F-206 has two stationary platforms opposite each other, so two of the reflecting surfaces could be positioned at 20° by having the laser mounted on one platform hit a photodiode mounted on the opposing platform. The laser mounted on the middle platform needed to hit the photodiode mounted on the same platform, so the reflecting surface on the pyramid mirror needed to be much steeper than the other two.

One other experimental setup that would be possible is incorporating the sensor into the HexFlex structure to allow for quick and easy measurements of the nanopositioner stage. The measurements would be taken in the same manner as on the F-206, but with the mirrors and lasers evenly spaced 120° apart. This would require a few modifications to the existing HexFlex
design, namely removing the cap plate and expanding the inner hexagon part to accommodate the attachment point for the laser mounts.

Figure 6.6: Solid model of the experimental setup on the HexFlex.
Figure 6.7: Part drawing for the HexFlex laser mount.

Figure 6.8: Part drawing of the modified hexagon piece.
REFERENCES


