Department of Precision and Microsystems Engineering

6-DoF stage position measurement concept for microscopy with one 2D position sensitive detector (PSD)

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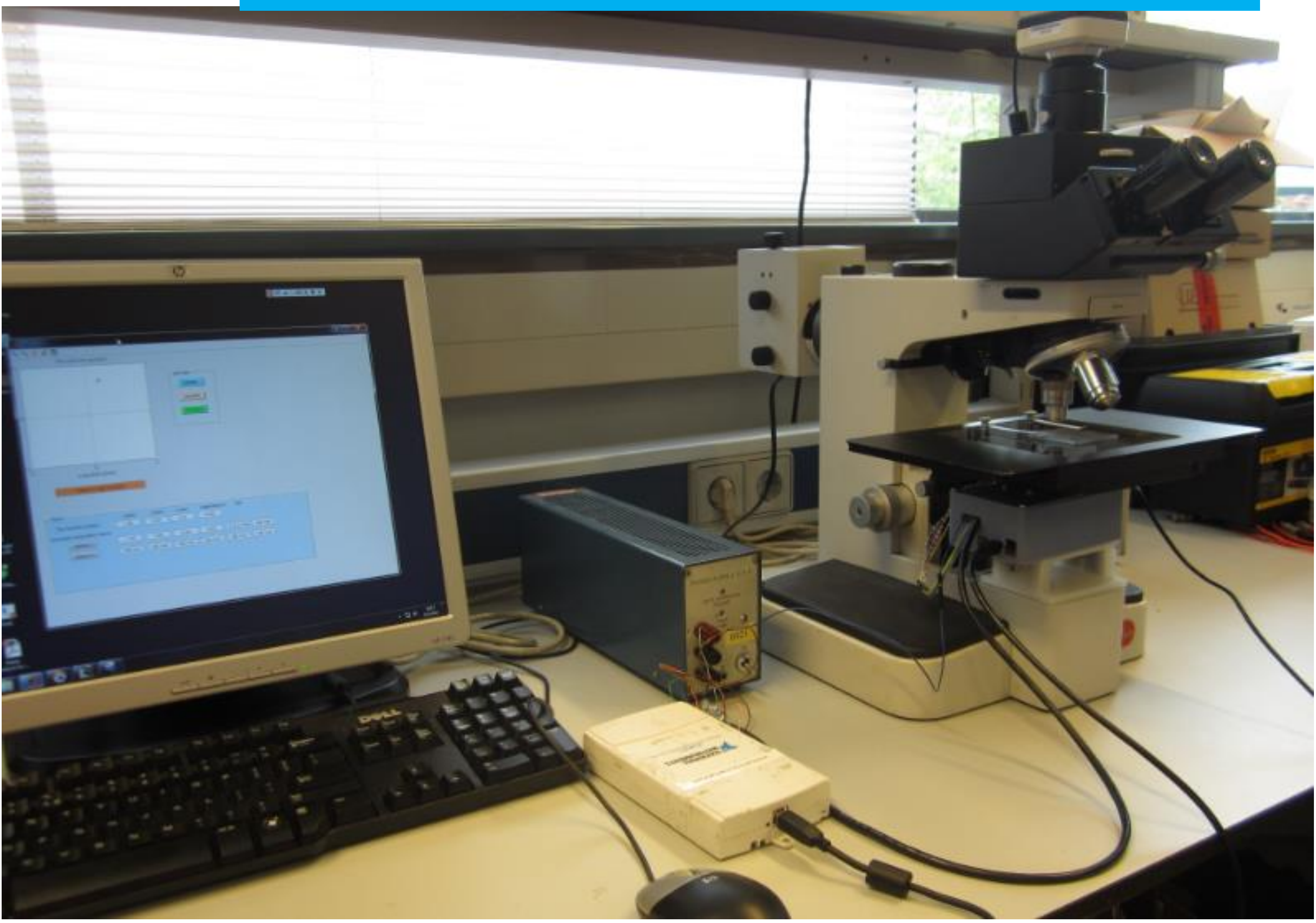

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Abstract

Mechanical, Maritime and Materials Engineering
Precision and Microsystems Engineering

Master Thesis

6-DoF stage position measurement concept for microscopy with one 2D position sensitive detector (PSD)

by Xiangyun He

Background Interferometers and capacitance sensors were used to measure the motion of the 6-DoF ferrofluid planar bearing positioning stage designed by Max Café who was the master student graduated in 2014. The sensor costs almost 30,000 euro to achieve nanometer scale accuracy. However, in some biology applications, such as observation of normal cells, the tens of micrometer scale accuracy and repeatability is good enough. That's why investigate a cost effective concept to measure the stage motion is needed.

Objectives The first aim of this project is to design a 6D measurement concept. The second aim is using a normal microscope (3D) to demonstrate the performance of this measurement concept, finding back the interested cells under the microscope. The third goal is to prove the whole system can achieve 10 μm repeatability, within 1000 euro.

Methods After researching the position sensitive detector, the measurement concept is developed from 2D to 6D. The measurement system consists of LEDs, a pinhole, a 2D-PSD, the Arduino Uno or Due, National Instruments data acquisition box (NI) and a laptop. A test setup was built to show the 4D measurement concept. Finally, the sensor system including the electronics was built and validated on a microscope.

Results and conclusions The result shows that based on theory (algorithm) the 6D motion measurement can be achieved in the future. Two microscope setups were built in the demonstration. The setup using NI proves the system can achieve 2 μm repeatability and 10 $\sim$ 20 μm accuracy within 1800 euro cost and the setup using Arduino Due proves the measurement system can achieve 15 μm repeatability and 10 $\sim$ 20 μm accuracy within 900 euro cost. In addition, the graphic user interface helps the users to find back the cells effectively.

Acknowledgements

Hereby I would like to express my gratitude towards those who contributed directly and indirectly to this thesis:

Foremost, I would like to thank my supervisor Professor Rob Munnig Schmidt for giving the very educational lectures and introducing me to Jo Spronck.

I would like to thank my daily supervisor Jo Spronck, who gives me valuable instructions both on academic and personal level. I am extremely lucky to have a supervisor who influences his students by his positive attitude. What's more, he can stand in my culture perspective to understand my question and explain it in my way. At the same time, he tells me what a western people will think of my question and where I could adjust the way of expression, which will be really valuable in my future career life.

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Also special thanks to one of my best friends Ruijun Deng, for her support and encouragement on my study and life. She also took time on proof reading of my thesis.

There is also appreciation for my energetic fellow students, Stefan van der Kleij, Gihin Mok, Paul Ouwehand and Charlie van der Schoor helping me acquaint with the softwares they commonly used and the tools in lab.

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Thanks all the MSD family members who make this study life full of love and happiness, which must be the most memorable experience during my overseas study life.

Last but not least, I would like to thank my loving parents for supporting me to study overseas. And also thanks for my friend Fei Chen and my boyfriend Xiuyu's constant support and care.

Contents

Chapter 1

Introduction of microscopy measurement system

1.1 Background

A 6-DoF ferrofluid planar bearing positioning system in our mechatronics lab is designed by Max Café [1].In order to measure the motion of the bearing, the interferometers and capacitive sensors were used in his project which cost almost 30000 euro to achieve 10 nm accuracy. While, moving the stage into the required position, the position information from sensor is indispensable. That's why investigate a cost effective concept to measure the stage motion is needed.

For biologists, finding back the interesting cells under the eyepiece is not an easy thing as shown in Appendix D on page 57, especially when the neighbor cells all look similar. Because the normal animal and plant cells diameters are between 10 to 100 μm shown in Figure 1.1, the ten micrometer scale repeatability is enough to find them back.

In the field of microscopy, the three directions x, y and z (height) are used frequently. The x and y direction detection is useful for observers to find object under the eyepiece. The z direction information informs user if the lens is in focus or not.

In addition, almost all the high magnification objectives are equipped with string-loaded retraction stopper that protects the front lens elements and the specimen from collision damage. This stopper is much expensive in an objective. Sometimes users continually move up the stage to find the focus point. They stop moving the stage until they feel

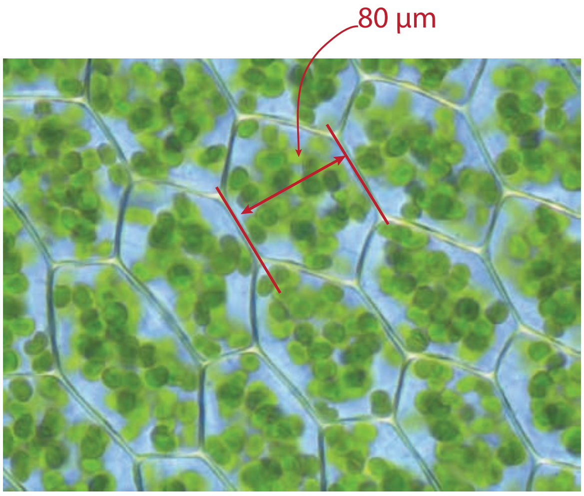


Figure 1.1: The normal plant cell sample.The normal animal and plant cells diameters are between 10 to 100 μ m, within 10 micrometer resolution is enough for finding it back.[2]

the objectives touch the specimen. This will short the lifetime of the expensive string-loaded retraction stopper, and even worse damage the lens and liquid sample. That's the reason why the z height detection is so important. Recently, optical position detecting technology is rapidly developed and widely used in industrial manufacture, instruments assembly and so on. There are many kinds of optical positioning detector, such position sensitive detector (PSD), CCD (charge- coupled device). Compared to CCD, PSD have features, such as high position-detecting precision, no focusing need, and no dead -zone of measurement.[4]

The linear PSD can be applied into one degree of freedom motion detection. The two-dimensional PSD have two different types: the duo-lateral PSD and the tetra-lateral PSD. The duo-lateral PSD has a higher position resolution, so that the duo type is used in this whole project. This duo PSD was bought by 770 euro 9 years before. I found the tetra-lateral PSD costs 50 euro in Hamamatsu company. If this type of PSD can be implemented in the system in the future, the cost can be reduced dramatically (see details on Chapter 5). The term PSD mentioned in following text all means the duo-lateral PSD.[7]

In Iwao's paper[11], he used three PSD to measure x, y(150 μm accuracy) and rotation (100u rad accuracy). Because the PSD is the most expensive part in the whole measurement system, minimize the PSD number is a way to reduce whole cost.

1.2 Assignment

The assignment for my thesis is as follows:

• Develop a new 6-DoF measurement concept which can be integrated with the 6-DoF planar stage in the future.

• Integrate the sensor system on a microscope to demonstrate the measurement concept. Design a interface to help users to find back the interested objects (cells) under the microscope.

Table 1.1 illustrates the system specification. The x and y direction detection are more important when finding back interested cells. The z direction detection information helps user to find the focus point. And the planar rotation θ_z detection is for planar control the planar stage in the future.

Knowing the real value is not much important in this finding back system, because finding back the cells based on the history coordinates of the cells. Compared to the accuracy, the repeatability is much more important to this finding back system. Ideally, the microscope should go to the same position as the previous time, which can show prefect repeatability.

At the beginning of this project, Jo set the assignment of finding back a normal plant cell with the diameter of 80 μm. The happy thing is the repeatability of this measurement system can achieve 10 μm, which means we can finding back much smaller objects, such as bacteria. Then I change this assignment's specification repeatability error to 10 um .

TABLE 1.1: System Specification need for the microscope application

Specification	Value
Measurement ranges	x:10 mm y:10 mm z:2 mm θ_z:360 degree
Degree of freedom	2D to 4D
Accuracy	$< \pm 20\mu m$ (x,y direction); 0.1 degree(θ_z)
Repeatability	$< 10\mu m$
Measurement speed	0.2s
cost	< 1000 euro

The components specifications are described in the Appendix A. The system specifications achieved are shown in the Chapter 5.

1.3 Overview of thesis

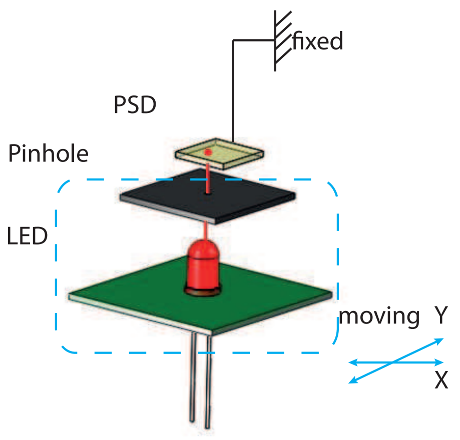
This thesis describes the how the concept develops from 2D to 6D step by step. Further more, focus on how to apply the measurement concept on a normal microscope. Chapter 2 describes the design steps and schematically shows each design setup. Chapter 3 illustrates the pre-experimental setup and validation results. In chapter 4 two microscope setups are introduced. The conclusions and recommendations are stated in Chapter 5.

Chapter 2

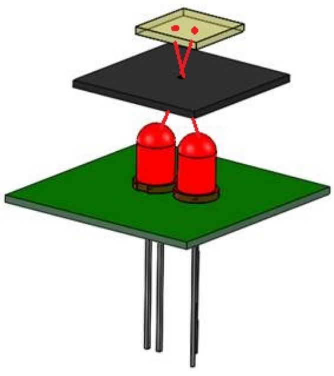
Concept design

This chapter first describes the concepts developed from 2D to 6D by distributing LEDs in different patterns. Each LED pattern design has its own measurement range and measured numbers of degree of freedoms. Second, the whole measurement system is introduced, including sensing element, signal processing element and data presentation element.

2.1 Concept development: from 2D to 6D



(A) 2D concept

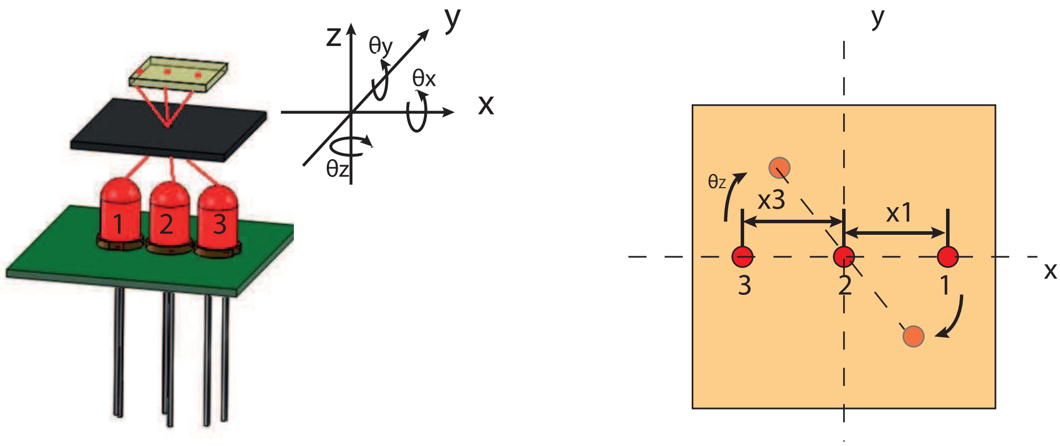


(B) 4D concept

FIGURE 2.1: These two pictures show how the measurement concept developed from 2D to 4D. Based on the optical path theory, (A) structure can detect 2D motion x and y both with range 10 by 10 mm.(B)structure can detect 4D motion x and y both with range 10 by 10 mm, planar rotation 360 degree(when two light both in the active range)

.

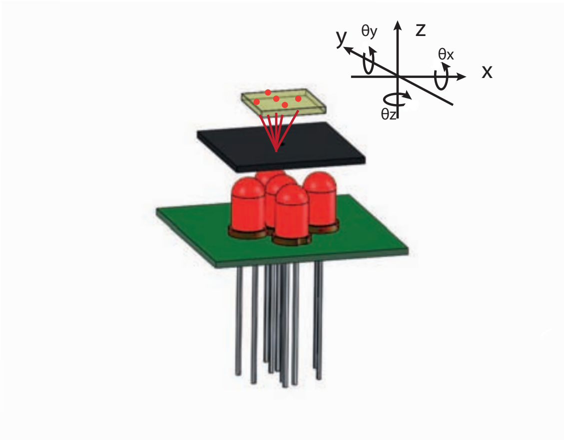
As shown in Figure 2.1, the developed steps from 2D to 4D detection are introduced. The LED and pinhole board are fixed on a moving stage, while the PSD is fixed on the ground. The position of the stage can be detected by the relative movement of the LED and the PSD sensor board. The detailed working principle of PSD is described in Section 2.2. Figure 2.1(A)shows only one LED in the center of stage. The stage and pinhole will moved together. At the same time, the PSD reads out the position of the light spot (x, y). (B) shows a 4D detection concept. Use one LED to detect (x, y). The distance between two light spots on the sensor will changed with the stage height adjustment,so the stage height z can be calculated. The rotation θ also can be obtained by the two LEDs coordinates. The limitation of this concept is when one of the LEDs comes out of the sensor active range, the z and θ can not be obtained.



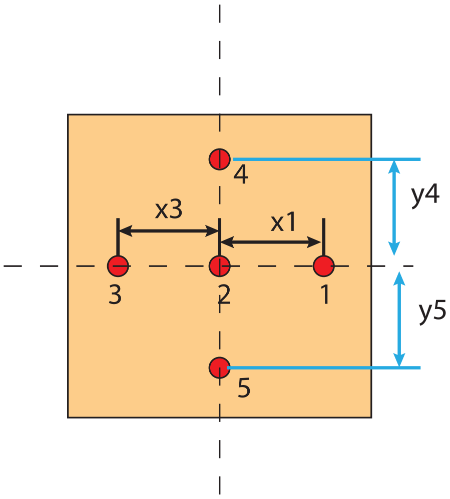
(A) 5D (B) The top view of PSD

FIGURE 2.2: 5D concept design contains 3 LEDs. This design is developed from Figure 2.1(B)by adding one LED

The Figure 2.2 shows the 5D measurement concept. Compared to Figure 2.1(B)design, this concept extends the measurement range. The LEDs are numbered from 1 to 3 from left to right. The light spots on the sensor are come from 3 to 1 from left to right shown in the top view of PSD. For simplify, the x_1 and x_3 represent the distance between the light spots. In this concept use LED2 to detect the stage position $x = x_2$ and $y = y_2$. If $x > 0$, use the coordinates of light spot 3 to calculate z and θ_z. Because by changing the stage height z, x_3 will change at the same time. The planar θ_z can also be calculated by the LEDs coordinates. The information of θ_y can be obtained from comparing the distance of x_1 and x_3.



(A) 6D



(B) The top view of PSD

FIGURE 2.3: 6D concept design contains 5 LEDs. This design is developed from Figure 2.1(C)by adding more two LED beside the center LED.

The Figure 2.3 shows the 6D measurement concept.This design contains 5 LEDs developed from Figure 2.2 by adding another two LEDs beside the center LED. By comparing the distance of y_4 and y_5, the θ_x can be calculated.

2.2 System schematic

The measurement system shown in Figure 2.4 consists of sensing, signal conditioning, signal processing and data presentation elements[8].

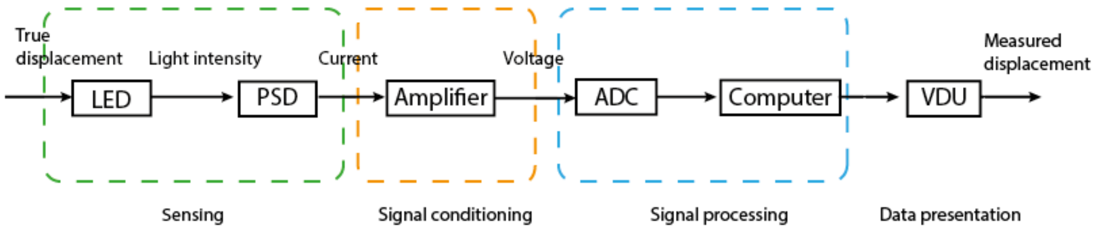


FIGURE 2.4: The position sensitive detector measurement system

Sensing element

Sensing element PSD converts the light signal into analogue electrical signal. The detailed working principle can be found in Section 2.2.1.

Signal conditioning element

The current to voltage amplifier circuit transforms four PSD output current signals into four voltage signals SumX, SumY, DiffX and Diffy, which will be used in coordinates calculation later in section 2.2.1.

Signal processing element

National instrument data acquisition box contains a Analogue-to-Digital converter (ADC) which converts the four voltage signals into digital form for the input to computer. The Computer (Matlab or Labview) calculates the x and y coordinates from the incoming digital data.

Data presentation elements

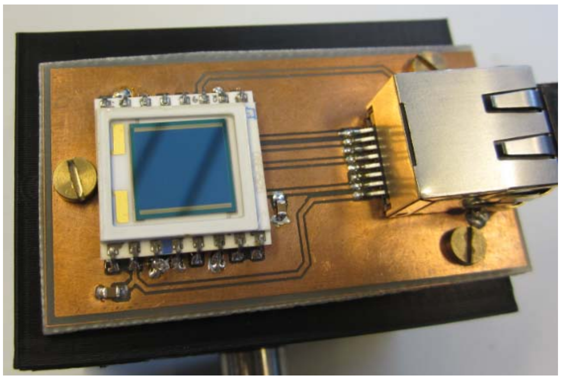
The data presentation element is the final element in the measurement system, which function is to communicate the measured position information to the user. The visual display unit (VDU) is a combination of a monitor and a keyboard. In this project, the monitor is operated under the Matlab software. I made the user interface to help users find back cells effectively.(see details on Appendix D page 59 and page 60)

2.2.1 Position Sensitive Detector (PSD)

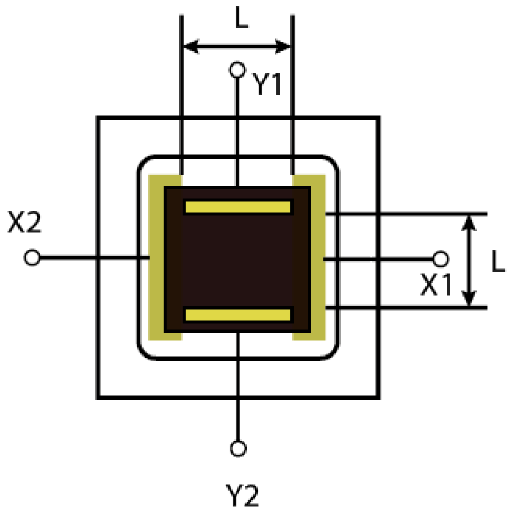
PSD working principle

The duolateral two-dimensional PSD $SiTek2L10_SPC01$ detects an incident light spot position on its square surface shown in the Figure 2.5.

The active area has a PN junction that generates photocurrent by means of photovoltaic effect[5]. The photoelectric current generated by the incident light flows through the device and is seen as two input currents and two output currents. The distribution of the output currents show the light position of one dimension (Y), and the distribution of the input currents show the light position of the second dimension (X). The equivalent circuit is shown in Figure A.2. With an attached signal processing circuit,the PSD currents are output as bipolar voltages representing the position and intensity of the centroid of a light spot on the PSD.[3]



] (A) The position sensitive detector picture



(B) Schematic of position sensitive detector

FIGURE 2.5: The left one shows the photo of the PSD. The right one is the schematic of position sensitive detector.[3] The photoelectric current generated by the incident light flows through the device and is seen as two input currents and two output currents. The amplify circuit is shown in Appendix A

The following formulas describe how to calculate the x and y coordinates by PSD sensor.

First, set the center point of the PSD as origin. The x direction position is calculated as follows:

$$I_{X1} = \frac{\frac{L}{2} + X}{L} \times I_X$$

$$I_{X2} = \frac{\frac{L}{2} - X}{L} \times I_X$$

$$X = \frac{I_{X1} - I_{X2}}{I_{X1} + I_{X2}} \times \frac{L}{2}$$

With

L=length of active area

I_{X1}=output current from electrode X1

I_{X2}=output current from electrode X1

Then after the current voltage amplification, the I_{X1}, I_{X2}, I_{Y1} and I_{Y2} transform into $V_{X1}, V_{X2}, V_{Y1}$and V_{Y2}.

So the x coordinates can be expressed as:

$$X = \frac{V_{X1} - V_{X2}}{V_{X1} + V_{X2}} \times \frac{L}{2}$$

As the integrated circuit's output signal Sum X and Diff X have following relation with the X1 and X2 electrodes output voltage.

$$SumX = V_{X1} + V_{X2}$$

and

$$DiffX = V_{X1} - V_{X2}$$

.

So the x position of the PSD is :

$$X = \frac{SumX}{DiffX} \times \frac{L}{2}$$

Similarly, the coordinate in y direction on PSD can be written as:

$$Y = \frac{SumY}{DiffY} \times \frac{L}{2}$$

The power dependency is canceled by taking the ratio of difference and sum value per axis.[9]

PSD resolution calculation

Position resolution is the minimum detectable displacement of a light spot incident on the PSD. Position resolution is expressed as:

$$\Delta R = L_x(\frac{e_n}{V_o})$$

Where,
L is the resistance length (Lx or Ly).
e_n is the output voltage noise. V_{p-p} or V_{rms}
V_o is the sum output signal level.
based on the PSD datasheet: the L=10 mm, e_n=3 mV_{p-p} and V_o= 12 V. so,

$$\Delta R = 10mm(\frac{3mV}{12V}) = 2.5um$$

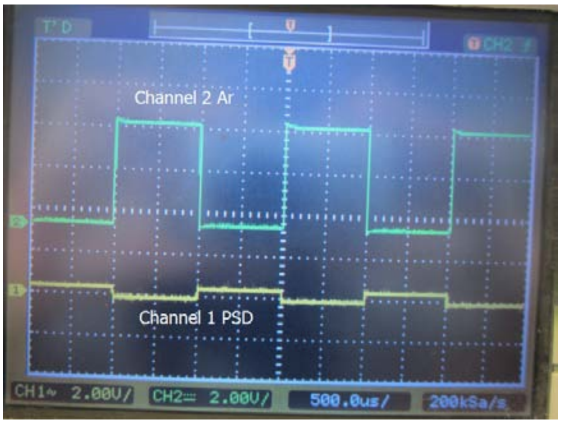
Power supply of PSD

From the PSD datasheet (Appendix A), the input voltage of PSD should be ±15 Volt. The following measurement was all conducted in this condition if no more illustration on the type of power supply.

PSD speed measurement

Figure 2.6 shows the step response of the sensor and the Ardunio. To confirm the sensor is fast enough for measurement, the settlement time of the sensor is tested. As shown in the Figure 2.6, channel 1 measures the PSD output voltage SumX and Channel 2 measures the LED supply voltage. The two channels both showed the square waves when the LED blink time is set as 1 millisecond. As shown in Figure (B), the settle time of sensor is about 10 μs.

Thus, if the led blink time is set longer than the sensor speed (10 us), the measurement can be performed well. This sensor is fast enough for the microscope findback application.



(A) The square waves

(B) Sensor settlement time is 10 μs.

FIGURE 2.6: Channel 1 measures the PSD output voltage SumX and Channel 2 measures the LED supply voltage. The two channels both showed the square waves when the LED blink time is set as 1 millisecond. Then zoom the time into 5 us, the difference of the settle time can be seen directly on the oscilloscope.

2.2.2 Light source

In the lab, laser and LED are commonly used to illuminate light on the target. The following parts show how the laser and LED works, meanwhile the comparison of their advantages and disadvantages are explained.

Laser

A laser is a device that emits light through a process of optical amplification based on the stimulated emission of electromagnetic radiation.

LED

A light-emitting diode (LED) is a semiconductor light source. A LED consists of a chip of semiconducting material doped with impurities to create a P-N junction. When a light-emitting diode is switched on, electrons are able to recombine with holes within

the device, releasing energy in the form of photons[15].
The resistor in series with LED can be calculated as following:

$$R = \frac{V_s - V_f}{I_f}$$

where,
R is the resistor in series of LED.
V_s is the power supply voltage.
$V_f$is the LED forward voltage.
I_f is the LED forward current.
The comparison of laser and LED are shown in the Table 2.1.

TABLE 2.1: Laser versus light emitting diode

Type of light source	(dis)advantages	
Laser	advantages	monochromatic (single color wavelength)
		collimated (non-divergent)
		coherent (wavelengths in- phase)
		higher power
	disadvantages	much higher cost
		eye hazard
LED	advantages	Less invasive, safer
		Lower cost
		have larger emitting regions
	disadvantages	lower power
		Less precise wavelengths

It can be concluded that the LED is chosen as the light source in the project, because positioning the LEDs on the circuit board is easier than aligning the Laser. What's more, LED is at low cost and safe.

2.2.3 Pinhole

The main purpose of this experiment is to determine how the major factor like geometry and mechanical factor exert an effect on the light spot power. Because the value of output voltage is influenced by the light spot position, the spot power, and ambient light. There is need to know which parameter influence the spot power target on the sensor.The LED and pinhole structure is shown in Figure 2.7

The power out of the pinhole is P_{out}:

$$P_{out} = \frac{p_{Led} \times S_p}{S}$$

where the

$$S = \pi R^2$$

and

$$R = d \times tan\theta$$

$$S_p = \pi r^2$$

So the power out of the pinhole can be expressed as:

$$P_{out} = \frac{p_{Led} \times r^2}{d^2 (tan\theta)^2}$$

Where r is the radius of the pinhole, S is the projection area, S_p is the area of the pinhole. d is the length between the led center and the pinhole plate.

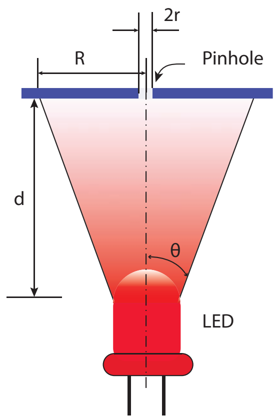


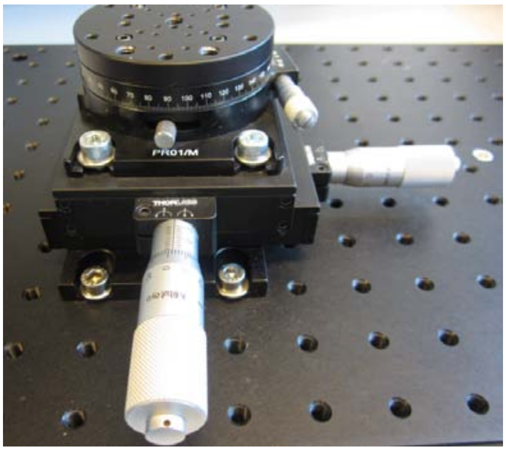
FIGURE 2.7: The power comes out of the pinhole can be expressed as the above equation. That is to say, the position of pinhole and Led, the size of the pinhole, and the spot power all influence the power coming out of the pinhole, which will influence the output voltage of sensor.

It can be concluded that power supply of the sensor, type of light source, LED view angle, pinhole position and size, the resistors in series with the LED all will influence the spot power target on the sensor. Based on these parameters the 4 mW power LED with 20° half view angle (see specification in Table A.2) is selected. The power comes out of the pinhole is about 0.1 W which is enough for PSD detection.

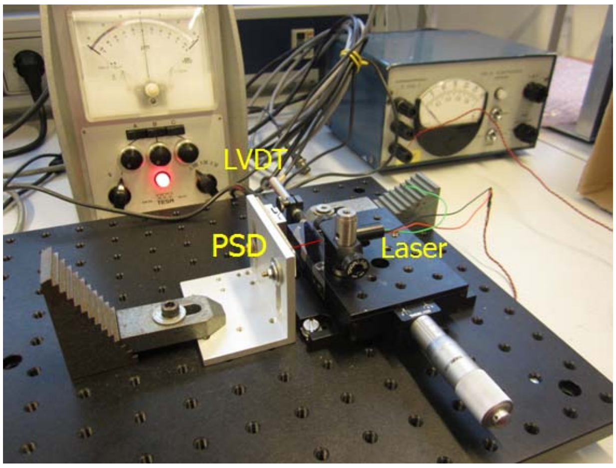
2.2.4 Stage

The Thorlabs stages shown in Figure 2.8(A) is used in the project. And the linear and rotation stages can be mounted to each other very easily. The linear stage is driven by the the micrometer with 25 mm moving range. In the longitudinal line of the frame is graduated with 1 mm divisions and 0.5 mm subdivisions. The resolution of micrometer is 10 μm.

Manual error As shown in Figure 2.8(B) To detect how large the manual error, the linear variable differential transformer (LVDT) sensor is applied to the stage.



(A) The Thorlabs stages



(B) The simple linear stage

FIGURE 2.8: The laser is fixed on the linear stage. The linear variable differential transformer (LVDT) sensor is used to check whether the linear micrometer screw gauge is accurate or not. The resolution of the LVDT is 0.5 μm and the resolution of the micrometer is 10 μm.

TABLE 2.2: Measurement the manual error

Measurement	1	2	3	4	5	6
Readout(μm)	-3.2	-3	-3.1	-3.1	-2.9	-2.9

As seen from the Table 2.2 The mean value of the readout is -3.03 μm , so the moving the Thorlabs stage by hand will cause -0.17 to +0.13 μm uncertainty.

2.2.5 Data acquisition

NI 6008-12 bit and NI 6211-16 bit

Two different resolution National instrument data acquisition box were tested in the project. NI 6211 has more than 1000 times better resolution then 6008. Their data sheets are shown in the Appendix A. In the later description of the thesis, the NI all means the NI 6211.

Arduino Uno 10 bit and Due 12 bit

Arduino Uno operates with 5V while the Arduino Due operates with 3.3V. Uno provides 10 bit ADC capability while the Due provides 12 bit shown in Appendix A. Uno is used in pre-setup described in chapter 3. Due is applied in the microscope demonstration introduced in chapter 4. Choosing Arduino Due in the final demonstration has two reasons: First, Due has higher ADC resolution 12 bit. Second, when powering by a computer via a USB cable, the Due operating voltage (3 mV_{p-p} noise) is more stable than that of Uno (10 mV_{p-p} noise), because Due has the on board regulator to stabilize the voltage from the computer.

2.2.6 Visual display unit (VDU)

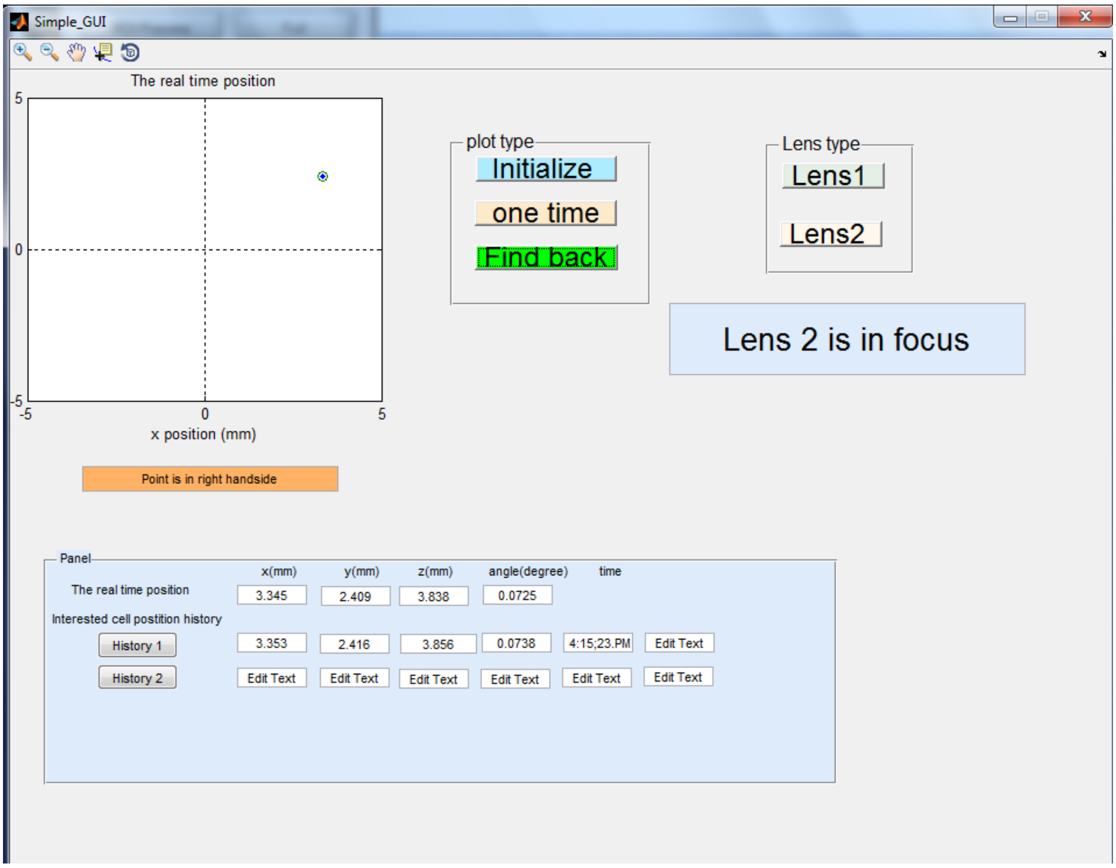


FIGURE 2.9

I made a user interface for the microscope find back application as shown in Figure 2.9. There are several panels on this interface. The user can choose to do one time measurement or loop measurement. After the user chooses the lens type, the message of if the lens is focus in or not will be displayed in the message box. If the height of stage is very close to the objective lens, it will display the warning message.

When the user finds an interested object under the microscope, he need click the history 1 button. Then the coordinates of stage will be displayed in the box. In addition, the measurement time will also be recorded. The rightest box is designed for note-taking, especially when users want to write down some important description during observation.

The user continues observation by moving the stage to other position. When he starts to find back, the history coordinates (circle $\bigcirc$) and the real time coordinates (point $\bullet$) will be displayed in the plot window. The user need to adjust the microscope x and y stages until the point is in the center of the circle. Then the user can see the interested object is just under his microscope.

This **circle $\bigcirc$ and point $\bullet$ find back method** is the second edition interface designed near the end of the work. The first edition interface only contains the real time and history digit coordinates recorded in the series boxes. The user need to compare the coordinates when he is adjusting the stage. Using this digit find back method cost about one minute, because the user need to calculate the difference of the coordinates by heart. Then a new graphic method suddenly came to my mind. This is really like **shooting the arrows at the target** $\odot$. This method only cost 20 seconds for users to find the object back with ten micrometer repeatability.

Chapter 3

Pre-setup and concept validation

Chapter 2 Figure 2.2 shows three LEDs in line model for the 5D detection. The x, y, z and θ_z, 4 Degree of Freedoms are validated in this chapter. The θ_y direction can be validated in the future. If this 5D concept can be proved to work, the 6D concept also be proved, because of the same working principle.

This chapter will discuss the setup for the 4D concept and calculation algorithm. The x position detection is preformed during the test and y position detection has the similar performance because the y and x direction detection have same working principle. The small-and large-range fittings are compared in the results. The second part of this chapter describes the error analysis.

3.1 Setup of three LEDs in line

The pattern of three LEDs in line is chosen to validate the 4D concept. As shown in Figure 3.1, Ardunio Uno is used to control the light blink and NI is used to do the data Acquisition.

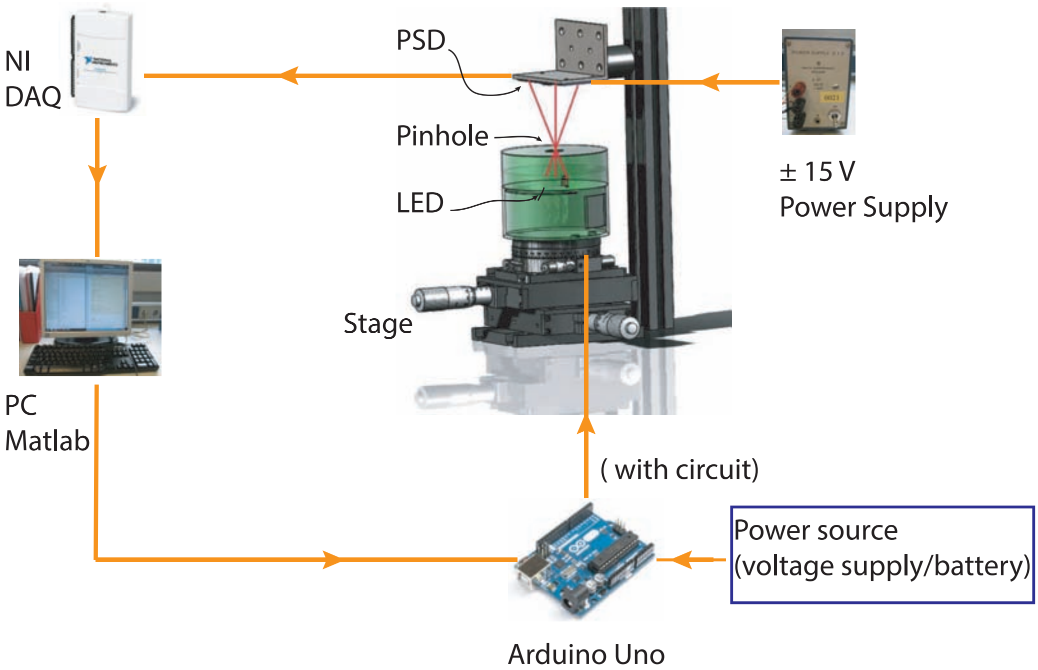


FIGURE 3.1: This is the first explanation setup. It shows the solidworks 3D drawing of the sensing elements. The LED box containing three inline LEDs can move with the 3D (x, y, θ_z) stage. PSD sensor is fixed on the right angle block which can adjust height along the vertical construction rail. Ardunio Uno is used to control the light blink and NI is used to do the data acquisition

3.1.1 Algorithm for 4D measurement

The flow chart shown in Figure 3.2 describes the measurement algorithm.
The positions of the light spots on the sensor are defined $(x_1, y_1), (x_2, y_2), (x_3, y_3)$, coming from LED1, LED2 and LED3 respectively. The position of the stage can be expressed as: (x, y, z, θ).

First, start the initialization (open the software Matlab, NI, Arduino.). Then use LED2 coordinates to determine the stage x and y position. After that judge if $x >= 0$ or $x < 0$, which means the LED2 in the right hand plane or left hand plane, respectively. If $x >= 0$, use LED1 to calculate the height and the angle. Otherwise use LED3.

$$height \propto \sqrt{(x_1 - x_2)^2 + (y_1 - y_2)^2}$$

$$\theta_z = arctan(\frac{y_1 - y_2}{x_1 - x_2})$$

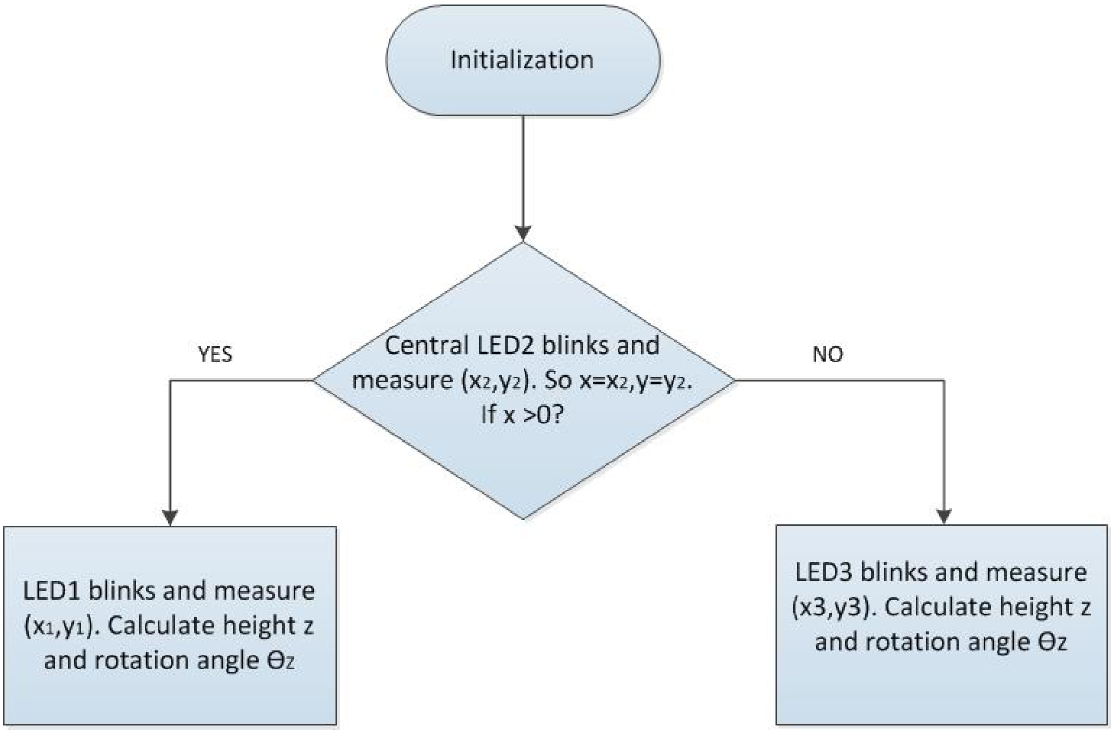
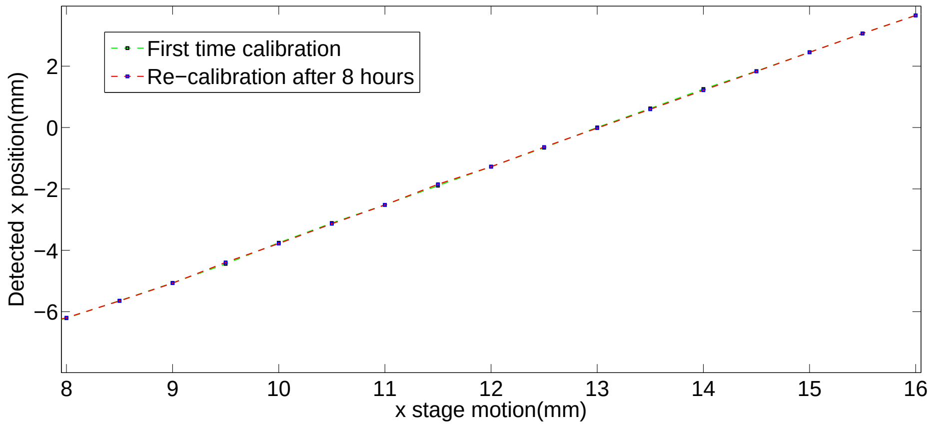


FIGURE 3.2: 3 LEDs (4-DoF measurement) algorithm flow chart.First start the measurement,initialization. Then use LED2 coordinates to determine the x and y position. If $x >= 0$ use LED 1 to calculate the height and the angle. Otherwise use LED 3.

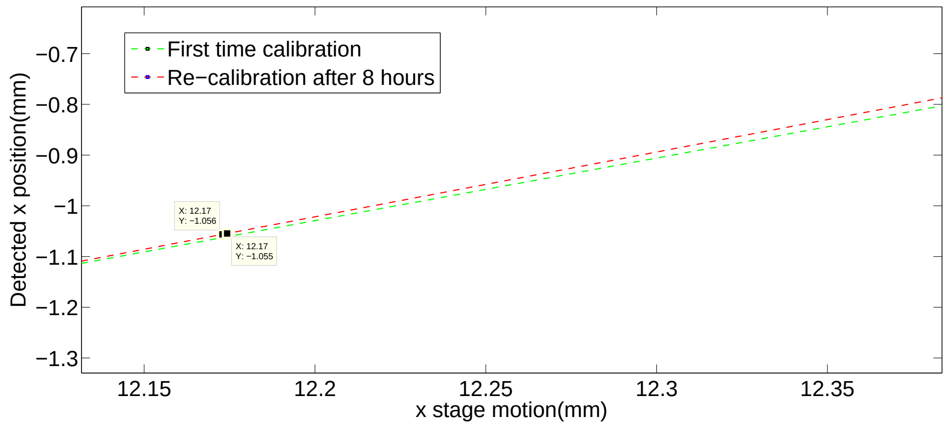
3.1.2 The x-translation calibration

During the calibration, the PSD detector keeps still and the moving stage drives the LEDs to move the spot on the photosensitive surface of the PSD. The measurement performance of the system can be evaluated by comparing the position value of the optical position detecting system output and the movement of the stage.

Long-term repeatability



(A) The two calibration curves of x direction were test in different time.

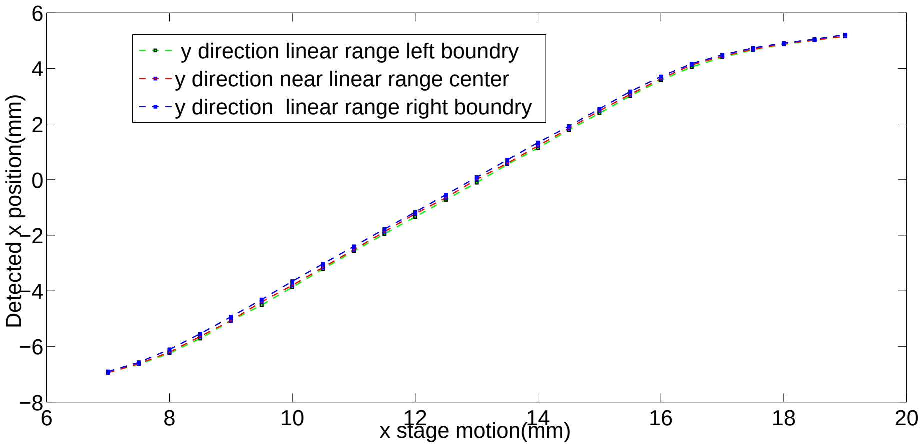


(B) The zoom in picture.

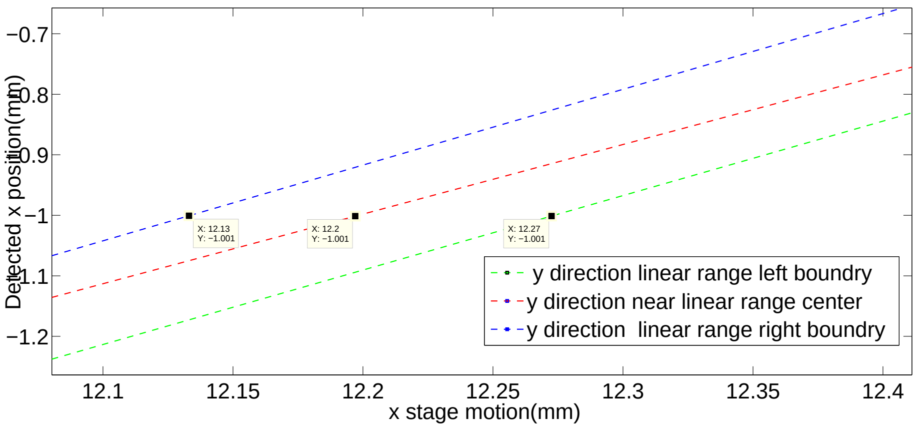
Figure 3.3: Figure (A) shows the two calibration curves of x direction. The zoom in picture is shown in (B). The distance between the two curves shows the 1 μm drift error.

Figure 3.3 shows the two times calibration curves of x direction. The second calibration is taken after 8 hours. The 1 μm distance between the curves is the drift error. This could be caused by the thermal drift of the PSD sensor.

Difference of the center and the boundary of the PSD



(A) The three calibration curves of x direction detection.



(B) The zoom in picture.

FIGURE 3.4: Figure (A) shows the three calibration curves of x direction. When the y stage is on the left ($y = -3mm$), un the center($y = 0mm$) and on the right($y = +3mm$) of the active area. The zoom in picture is shown in (B). The distance between these lines are 0.1 mm. This implies even though the output sensor shows the same x coordinate, the real x value has ± 0.1 mm difference.

In order to check the performance of this calibration in the active area center and boundary, we move the y stage to the left ($y = -3mm$), the center($y = 0mm$) and the right($y = +3mm$) of in the active area. Figure 3.4 shows these three calibration curves. The three calibration curves are not totally matched, the zoom picture shows even though the output sensor shows the same x coordinate, the real x value has ± 0.1 mm difference. This means there is an angle between the stage x y axis with the sensor x y axis. This indicates y direction calibration should take as the same time with x calibration (plane calibration). This new algorithm is introduced in Appendix B.

Small and large range measurements comparison

The smaller range (-10 μm to 10 μm) calibration is preformed by the LVDT sensor, which is in opposite place of the screw handle as shown in Figure 3.5. The reason why LVDT is in the center of the stage is that the measurement direction and the moving direction can be coaxial to reduce the abbe error.

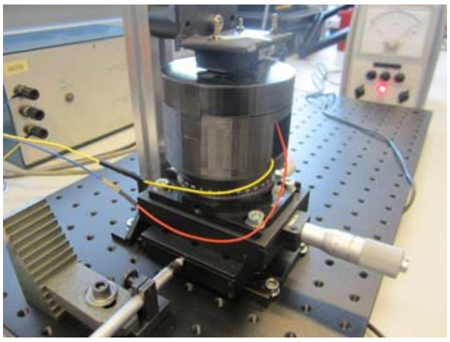


FIGURE 3.5: It shows the LVDT is in the opposite place of the screw handle to calibrate the PSD sensor in (-10 μm to 10 μm) range.

The 20 μm range calibration is performed from one direction (clockwise), because the mechanical hysteresis error will occur when the stage is moving to a same scale from clockwise or anticlockwise. As shown in Figure 3.6, the drift error is 2 μm in 20 hours in the active area center.

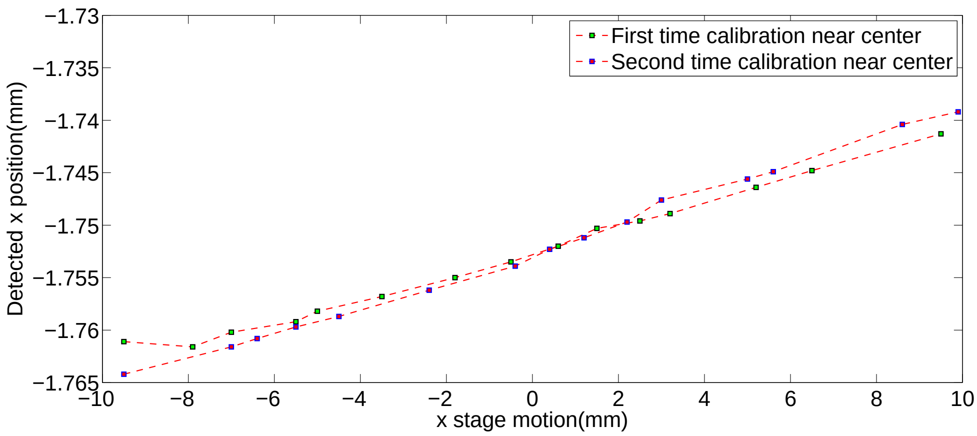


FIGURE 3.6: This figure shows two times small range(-10 μm to 10 μm)calibration. It is clear to see the system drift 2 μm in 20 hours in the sensor center.

The experiment different ranges (-8 mm to 8 mm), (-100 μm to +100 μm) and (-10 μm to 10 μm) are detected. Table 3.1 shows non-linearity of these measurements. It is clear to see that in the -10 μm to +10 μm shows the smallest first order fitting error 2.5 μm, which also indicates the smallest non-linearity. To calibrate the whole sensor range using the micrometer step by hand is time consuming. In the future this can be done by other high resolution sensors.

TABLE 3.1: Big range and small range non-linearity comparison

Polyfit	X	Y
measurement range	8 mm	8 mm
non-linearity error	$\pm$ 50 μm	$\pm$ 50 μm
measurement range	-100 to + 100 μm	-100 to + 100 μm
non-linearity error	$\pm$ 5 μm	$\pm$ 5 μm
measurement range	-10 to + 10 μm	-10 to 10 μm
non-linearity error	$\pm$ 2.5 μm	$\pm$ 2.5 μm

3.1.3 Planar rotation θ_z calibration

The rotation calibration is carried out by rotating the stage form 0 to 90 degree angle by 5 degree step size. The uncertainty of the moving stage by hand is ± 1 arc minute. Then used these following ten angles to validate my algorithm.

LED1 (left led) and LED2 (center LED) are usd to calibrate the stage rotation. It is concluded from the foregoing observations that the rotation detection error is within 0.07 degree after 2 hours, and 0.2 degree after 20 hours as shown in Figure 3.7.

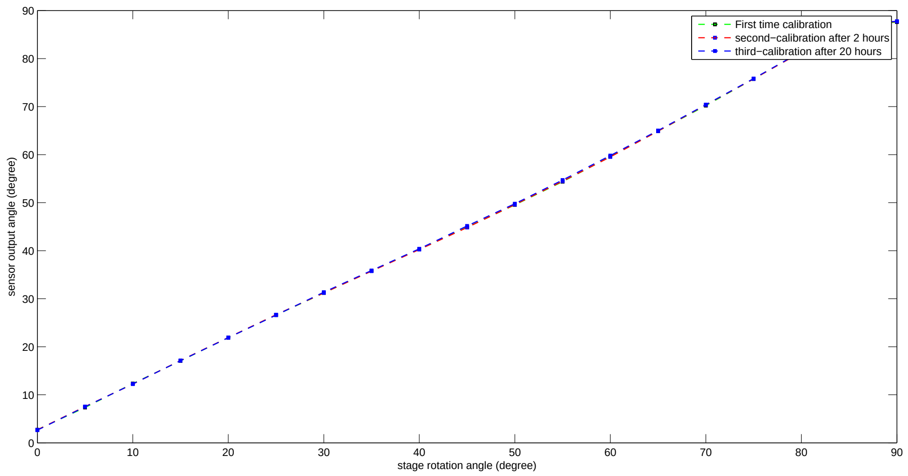


FIGURE 3.7: Calibration curve of the planar rotation. The curve shows three times results. After 2 hours, the second calibration was carried out.After 20 hours, the third one was preformed. The result shows the error is 0.07 degree after 2 hours, and 0.2 degree after 20 hours

3.1.4 Height z detection

This part is to prove the following height calculation formula, which shows the height of the stage and the distance between the light spot have the monotonic relation.

$$height \propto \sqrt{(x_1 - x_2)^2 + (y_1 - y_2)^2}$$

The caliper is used to measure the distance between the PSD and LED (represent the height). Change the sensor block position by moving the pillar on the construction rail. At the same time read out the distance between the light spots. From this simple measure, the monotonic relation can be proven. This indicates if a height stage is used which can readout directly by the scale, then the height of the stage can be calibrated. After the calibration, by reading out the distance between the light spots, the height of the stage can be calculated.

3.2 Error analysis

There are a lot of parameters influence the output results: the power supply of the Ardunio, the power supply of the sensor PSD, light noise, fitting error, manufacturing and assembly error, Sensor output noise, DAQ resolution, mechanical vibration, temperature fluctuation and electronic noise.

Power supply for Arduino Uno

This part compares the performance of Arduino Uno powered by computer via USB cable and voltage supply. The performance is evaluated by measuring the voltage output pin peak to peak noise on Arduino digital pin, which will power the LED circuit. The peak to peak voltage noises are 73 mV and 4.3 mV respectively. Figure 3.8 compares the sensor x position readout when Arduino is powered by computer via USB cable and voltage supply.

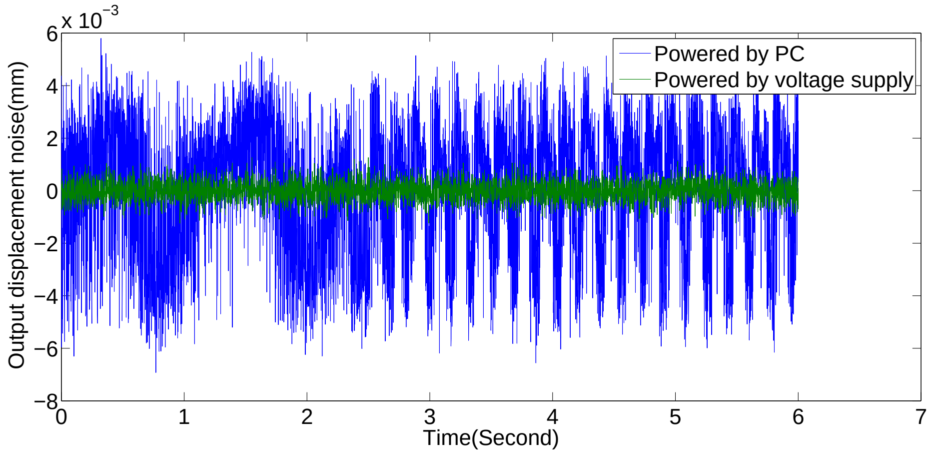


FIGURE 3.8: Compared to the result of powered by PC, the voltage supply gets a better result.

The Cumulative Power Spectrum (CPS) Figure 3.9 compares the output of Pin2 on Arduino powered by computer via USB cable and a voltage supply respectively. By taking the root of total value of the CPS, the standard deviation of the final error are obtained, 2.6 μm and 0.4 μm, respectively.

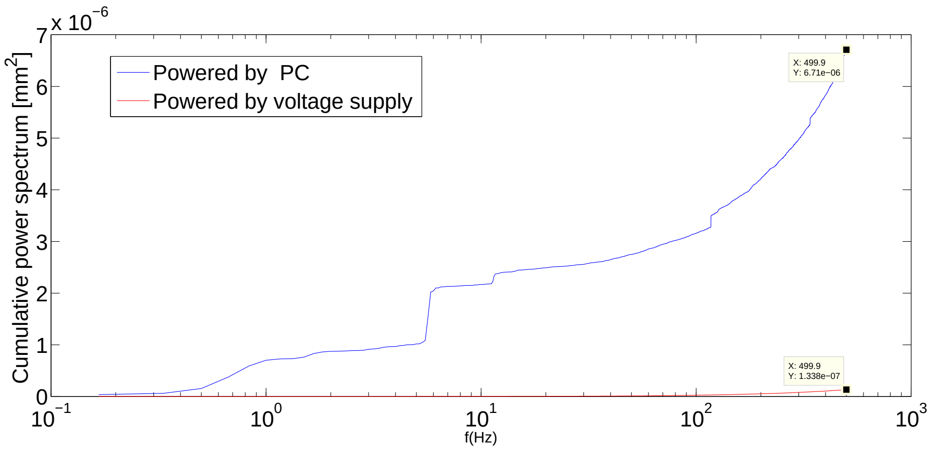


FIGURE 3.9: The CPS figure shows the significant influence of the 1 and 5 Hz noise from computer via USB. Based on the coordinate $(500, 6.2 * 10^-6)$, taking the root mean square of $6.2 * 10^-6$, the standard deviation of final error obtained is 2.6 μm.If Powered by voltage supply, taking the root mean square of $1.4 * 10^-7$, the standard deviation of final error obtained is 0.4 μm. So powered by voltage supply gets a better result than powered by computer.

Conclusion: Adding an external power supply (7 V to 12 V) to Arduino Uno can achieve 6 times better result compared with only powered by computer via USB.

Power supply for sensor PSD

From Woltring's point of view[9], if the duo-lateral photodiode is not fully reverse-biased, the relation between the output current and the light spot position will become non-linear, because the lateral effect will be influenced by the diode surface recombination. The reverse-bias written on the datasheet of this of kind PSD is 15 Volt. That's why the company suggests the user to use ± 15 V power supply.

However, from the comparison experiment of the power supply of the PSD shown in Table 3.2, even though the 9 V battery cannot make the photodiode fully reverse-biased, it achieves better result than the ± 15 V power supply does. The reason is the battery provides a more cleaner output voltage signal compared to the power supply due to the conversion from AC to DC[14]. When the 9 Volt battery drops to 7 Volt after using, it is also connected to PSD sensor to test the performance. It is clear to see that the sensor shows shows higher noise level by powered by 7 V battery than by 9 V battery, because of the serious diode surface recombination effect as Woltring [9] stated.

Table 3.2: Different power supply of PSD comparison

Power supply voltage	± 15 V power supply	± 9 V battery	± 7 V battery
Position noise level	4.4 $\mu m(p-p)$	3.6 $\mu m(p-p)$	3.9 $\mu m(p-p)$

Conclusion: It's safe to use the ± 15 V power supply to make the PSD sensor fully reverse-biased. If powering the PSD by battery, the voltage regulator are suggested to be added to keep the sensor supply voltage into a constant value. An alternative power block named low profile transformer is found on the RS website which only cost 12 euro.(see details in Chapter 5.)

Ambient light influence

The experiment of with or without paper shielding is performed to test the influence of ambient light when the LED in ”on” situation. Figure 3.10 shows the output displacement noise in time domain. (The mean value is subtracted from the data.)

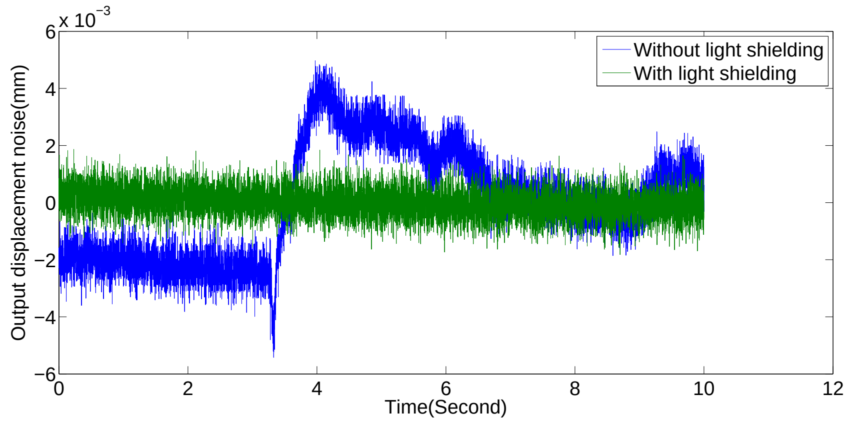


FIGURE 3.10: The picture shows the output noise of the x position with or without light shielding. The blue signal which has no light shielding has a obvious peak when a person pass by the system. The noise level can become 4 times smaller if the light shielding is added.

Conclusion:The ambient light influences the measurement performance. By adding a light shielding, the noise of sensor output can become 4 times smaller.

Fitting error

The largest contribution of the systematic error in this measurement system is the fitting error. The polyfit method is used in the curve fitting. Fit the two sets of data, one from the PSD sensor position readout, the other from the stage position readout. The errors for 7 order fitting x, y is $\pm$ 20 μm and the 3 order fitting for θ_z are -0.28 to +0.38 degree.

Manufacturing and assembly error

Some components used in experiments is printed by a 3D printer. The components have slight deformation because of the thermal effect during fabrication. There is also assembly error occurs after amounting all the components. For example, the x and y axis of manual stage is not aligned with the x and y axis of sensor. The manual stage plane is not parallel with the sensor plane. However,these errors are not relevant for repeatability, so they don't influence on finding back cells in plane. What's more, these error can also be compensated by appropriate algorithm.

Mechanical noise

Our mechatronics lab is located in a suspended structure. When standing in the lab, the low frequency vibration of the floor can be felt. Fortunately, the vibration signal is not found in the output of the sensor. The possible reason is the sorbothane feet under the Thorlabs Aluminum Breadboards isolate the table and the measurement system.

Chapter 4

Application example - Microscope 3D measurement

The measurement concept introduced in the previous chapters can be applied to the microscope observation to find back the object. This concept can also be applied to the stewart platform to provide the 6-DoF position information. Because of the limited project time, only Microscope application is validated here. This Chapter describes the detailed design decisions made to meet the requirements of the microscope stage based on the concept introduced in Chapter 3. This chapter focuses on the x, y and z coordinates detection. Furthermore, the possibility to make the whole structure at a low cost and compact is proven.

The measurement magnification is 1:1. The measurement concept can also be applied to a smaller range (magnification < 1) and a large range (magnification > 1). It is not possible to built the setup to investigate the other ranges performance in the time available for the project. Depending on the different measurement ranges, the lens of different magnification are required to implement into the setup.

The mounting procedure and component lists are illustrated in Section 4.1. The setups with National instrument DAQ box and with Arduino Due DAQ are introduced in Section 4.2 and 4.3. Appendix D 59 shows the detailed finding back procedure by using this demonstrator. Finally, the results of the two different setups were compared.

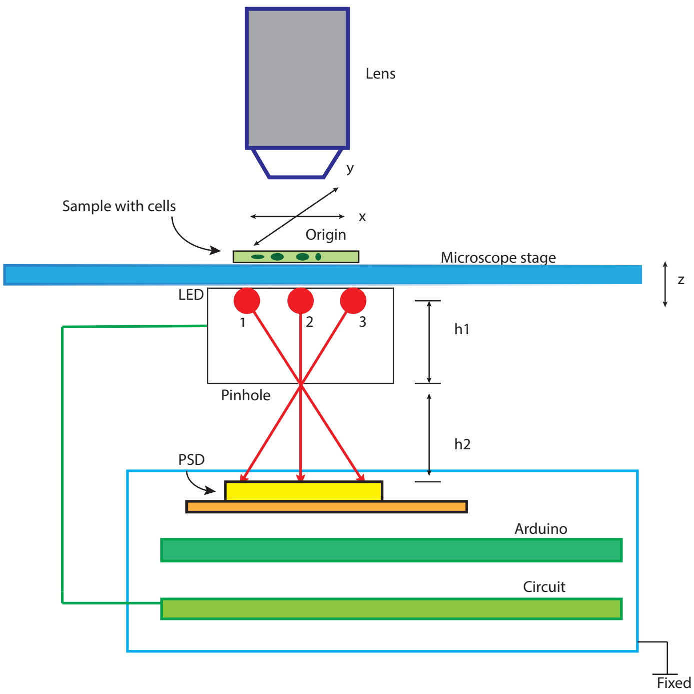


FIGURE 4.1: This figure shows the magnification of the sensor system is 1 by 1.

4.1 The Mounting procedure

Figure 4.2 shows the mount sequence of the measurement system and the components in the measurement system illustrated are shown in Figure 4.3.

The the PSD sensor box, LED box and the height adjustment connectors are all printed by 3D printer. The objective plate is made by laser cutting. The height adjustment connectors shown in the components list are the third edition of the design.(see details in Page 51)

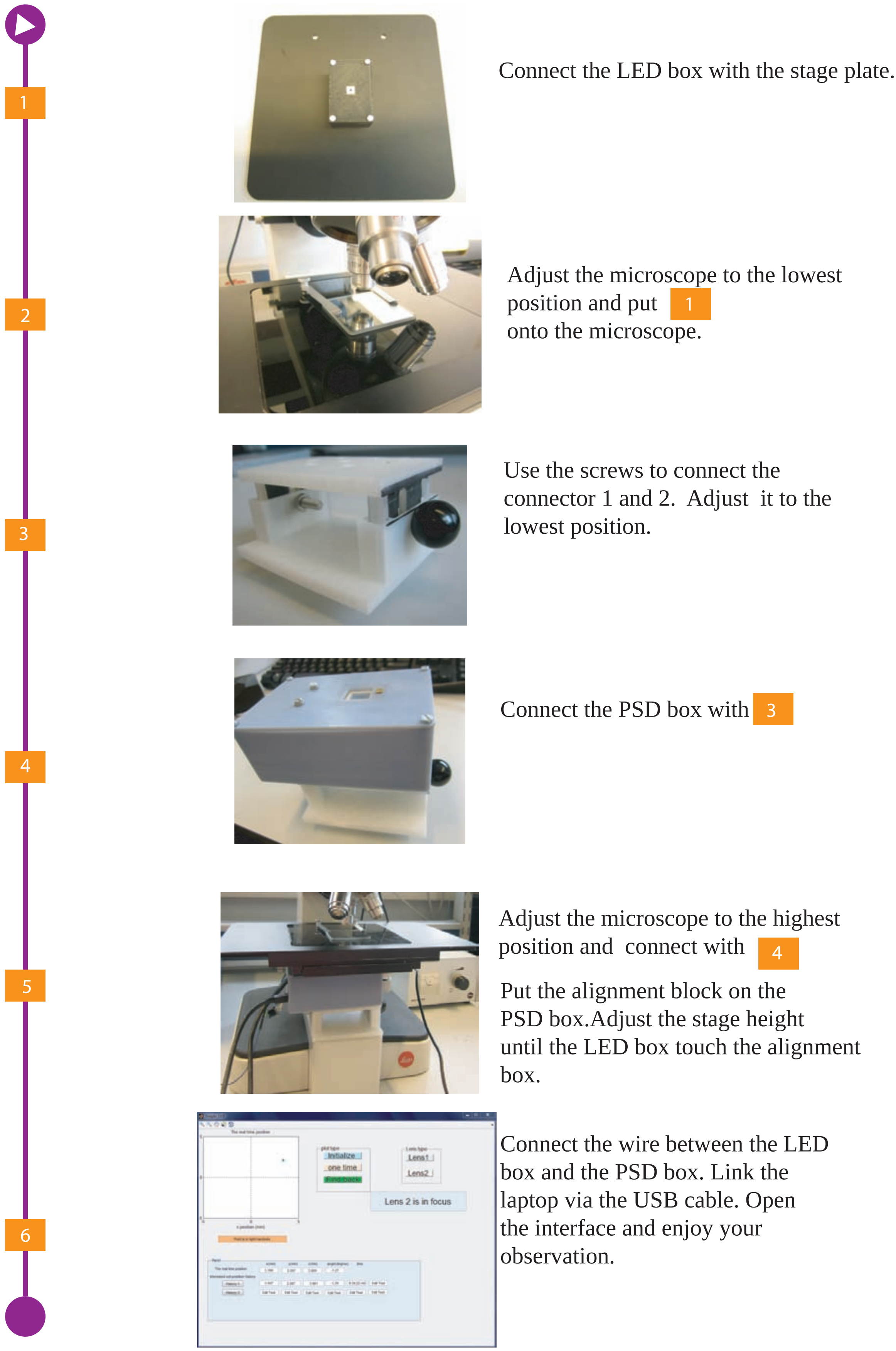


FIGURE 4.2: This figure shows the 6 steps of the mounting procedure of the measurement system.

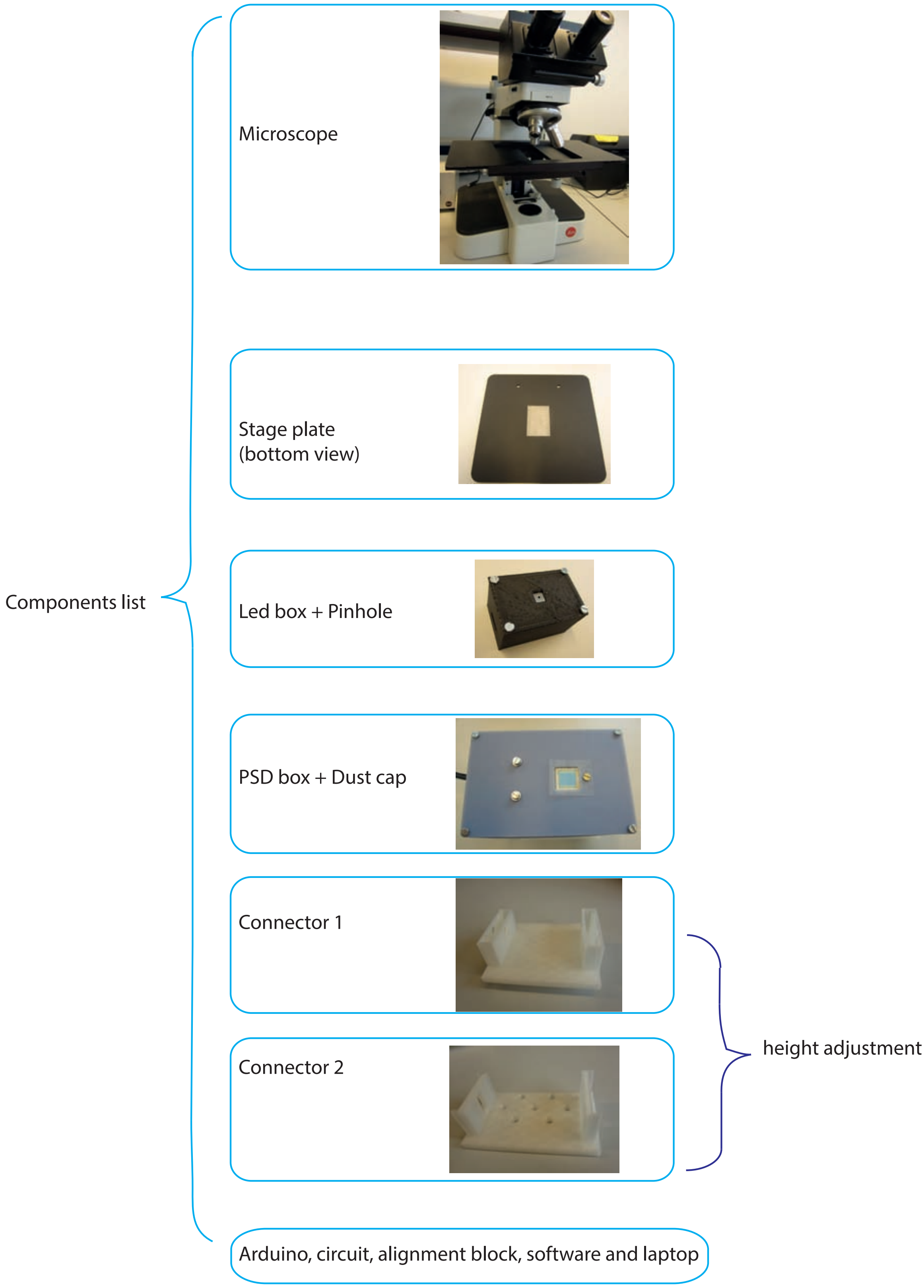


FIGURE 4.3: This figure shows all the components in the measurement system.

4.2 Setup 1 using National Instrument DAQ box

In the microscope application, the setup shown in Figure 4.4 similar to chapter 3 shown in Figure 3.1 is set. The Arduino Uno is replaced by Arduino Due. And a transistor circuit is made instead of a simple resistor circuit. (see some details in the Appendix A on page 47)

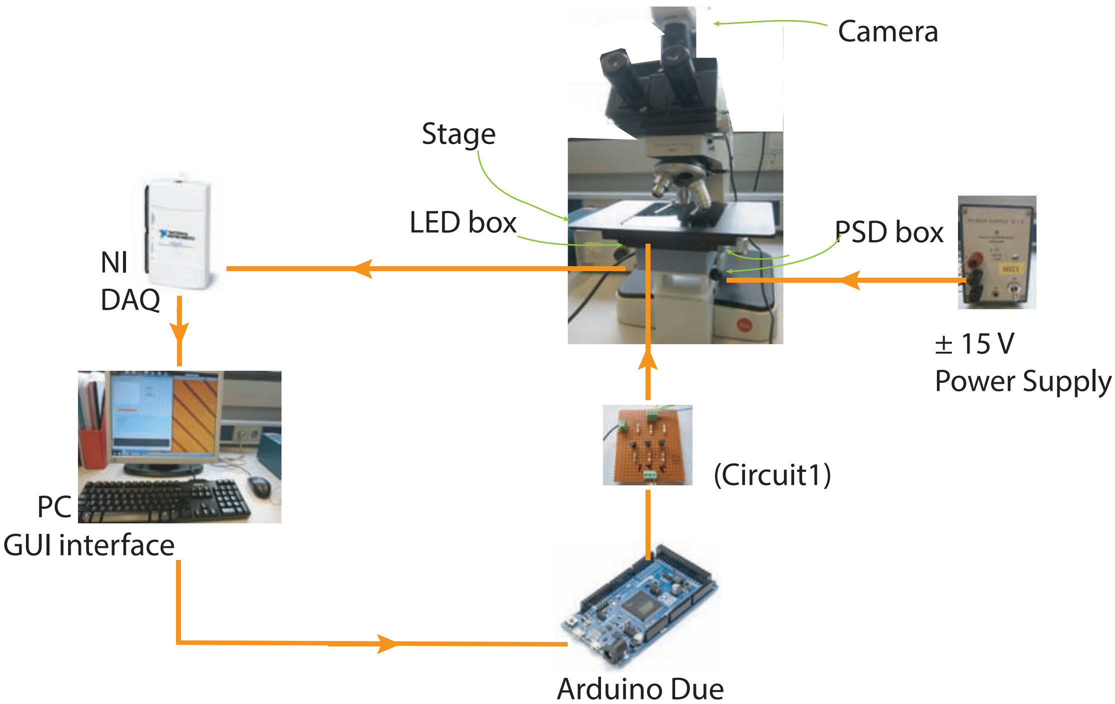


FIGURE 4.4: This sketch shows the whole microscope measurement system. The Arduino Due (**control LEDs**)and NI (**perform data acquisition**) are both connected to the PC via a USB cable. PSD sensor is powered by the $\pm 15V$ voltage supply. In order to show the user's view from eyepiece, a CCD camera is mounted on the top of the microscope. The circuit 1 is shown in Figure 4.5.

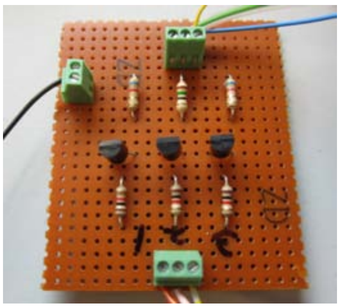


FIGURE 4.5: The function of circuit 1 is to switch the three LEDs on and off. (see more details in the Appendix A on page 47)

4.3 Setup 2 using Arduino Due DAQ

The designed product needs to be compact to satisfy customer's requirements. Also for the company, reducing the cost means more profit. Due to the aforementioned two points, the Arduino Due's data acquisition function is detected, as shown in Figure 4.6.

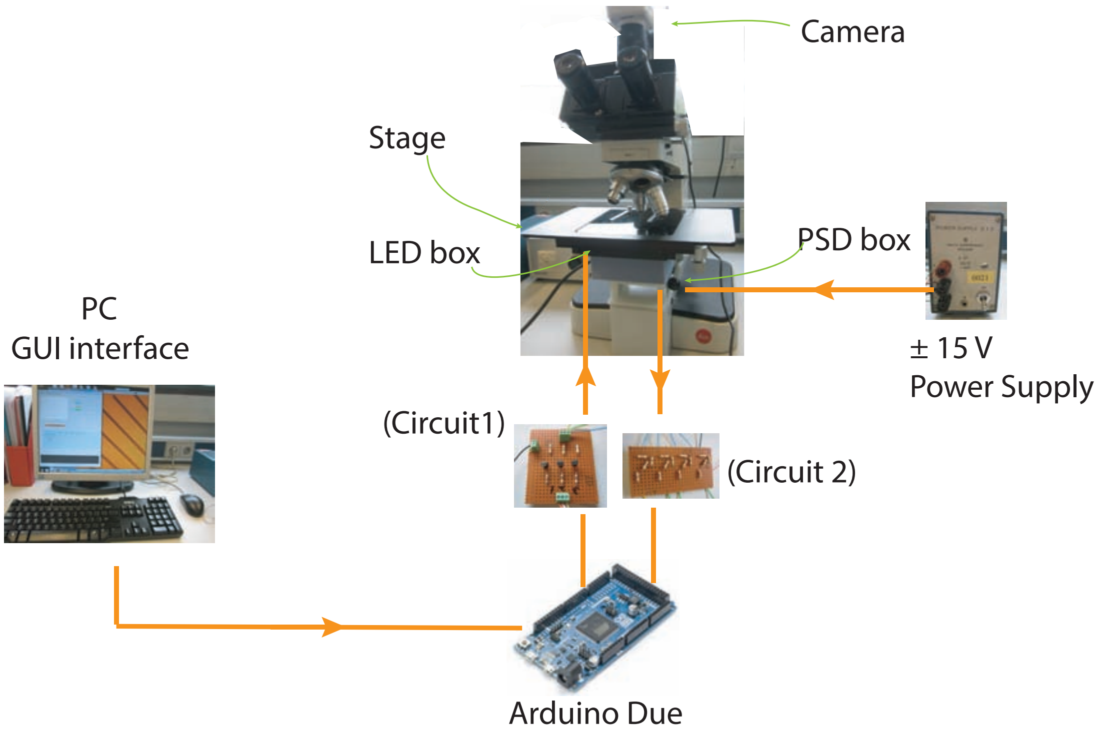
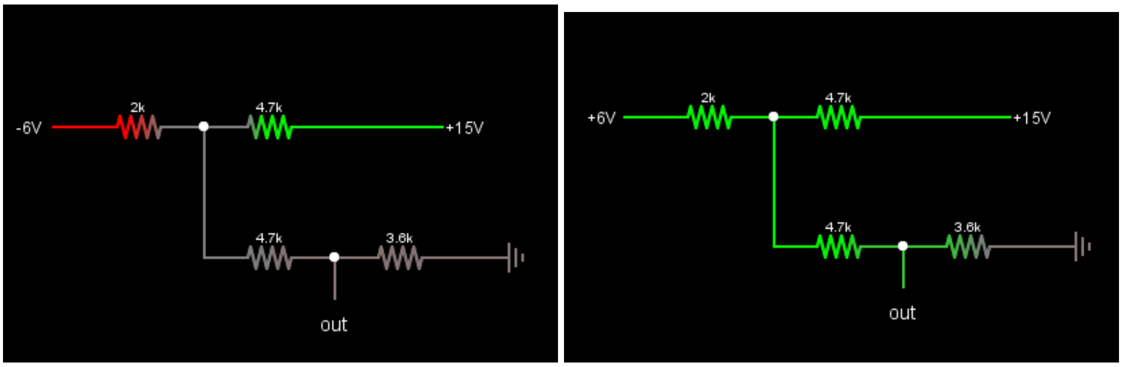


FIGURE 4.6: This sketch shows the whole microscope measurement system. The Arduino Due (**control LEDs and perform data acquisition**) is connected to the PC via a USB cable. The PSD sensor is powered by the $\pm 15V$ voltage supply. The circuit 2 is shown in Figure 4.8.

The Due analog input pins measure from 0 to 3.3 V. Applying more than 3.3 Volt on the pins will damage the chip. Following Figure 4.7 circuit transform the -6 to +6 Volt to the 0 to 3.3 Volt range.



(A) Circuit simulator $V_{out} = 0.1V$ (B) Circuit simulator $V_{out} = 3.22V$

FIGURE 4.7: This transform circuit changes the sensor output voltage from [-6 V, 6 V] to [0.1 mV, 3.22 V] which is within the Due data acquisition range [0, 3.3 V]. The resistors showed in the simulator are based on the resistors available in the lab.

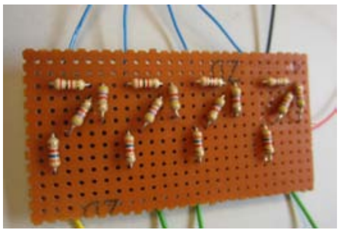


FIGURE 4.8: This is Circuit 2 . Four same transform circuits are made to change the four sensor outputs into Arduino data acquisition range

Measurement speed

It takes about 0.1 ms to read one analog input pin on Due (from the datasheet). However read out one analogpin on Arduino Due board through Matlab will take 8 ms. The main delay is due to the communication between these two software. Doing one cycle measurement takes about 52 ms. The human eye response time is about 0.3 second. That's why the 0.2 second pause time is added in the Matlab code for displaying.

4.4 Results

4.4.1 Results for Setup 1

This part describes how accurate the system is, and how large the find back error of the measurement is.

Error budgeting

The total error in the measurement system consists of the systematic error and the random error.

Systematic error

The systematic error is mainly caused by the fitting error. The planar calibration in the whole area as introduced in Appendix B is not preformed, because it is not needed in this find back demonstration. In the future for other degrees of freedom detection, that planar calibration will be implemented.

The rough calibration is done by the linear calibration ruler. Taking the step 100 μm of the calibration ruler as a reference, it shows $\pm 10\mu m$ error within the 6 mm range (Area 2) and $\pm 20\mu m$ error within the 9 mm range. Figure 4.9 shows the rough accuracy distribution over the active sensing area.

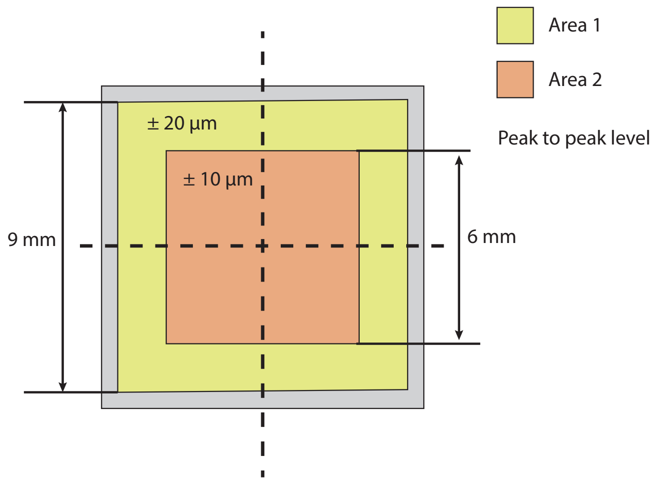


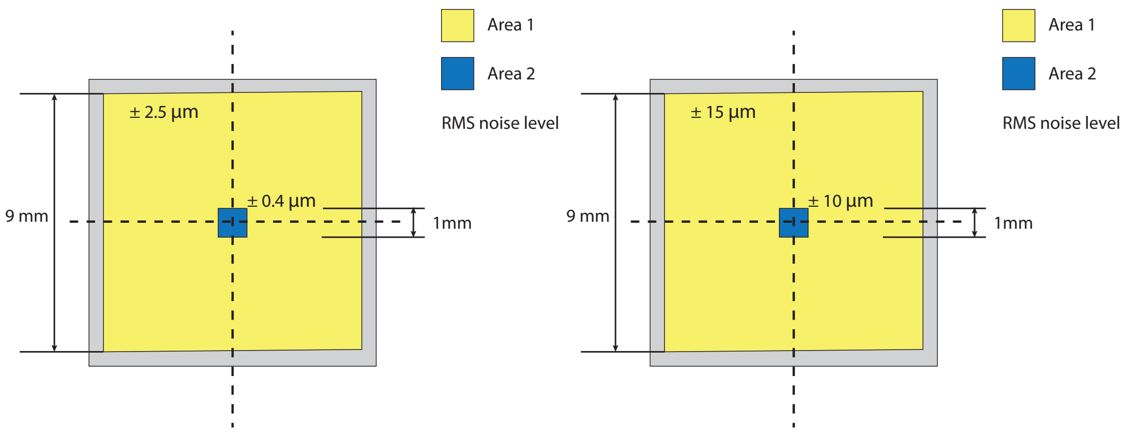
FIGURE 4.9: The accuracy of the sensor system. $\pm 10\mu m$ accuracy within the 6 mm range (Area 2) and $\pm 20\mu m$ accuracy within the 9 mm range (Area 1) were achieved.

Other systematic errors are mainly the manufacture error and assembly error. The surface of the 3D printing components is not flat due to the thermal effect. Also the sensor box plane is not parallel to the LED box and x y axes of sensor plane is not aligned with the x y axes in the stage plane due to manual assembly.

Random error

Figure 4.10 (A) shows the random errors in this measurement system. The minimum noise level is 0.4 μm within the 1 mm range in the center and the maximum noise level is 2.5 μm error at the edge of the 9 by 9 mm square. For simplify, only these two boundary values are shown in the figure.

The main random error is mainly caused by the power supply noise, the PSD noise.
- The Due power supply noise is 0.4 mV. [1]
- The PSD noise is 0.25-2.4 mV. (see details in Appendix C page 53)



(A) Random errors (B) Find back errors

FIGURE 4.10: This Figure compares the value of the random error and the find back error in the active detection area.

Find back error

As shown in Figure 4.11, the find back error consists of system random error and the user manipulation error. The manipulation error means the difference between the history coordinates and the findback coordinates. These definitions will be explained in an example later . Figure 4.10 (B) illustrates the find back error distribution over the measurement range.

[1]Since the position (length unit) is calculated by the quotient of two sensor output voltages as introduced in Section 2.1.1, the original unit was used to derive the error.

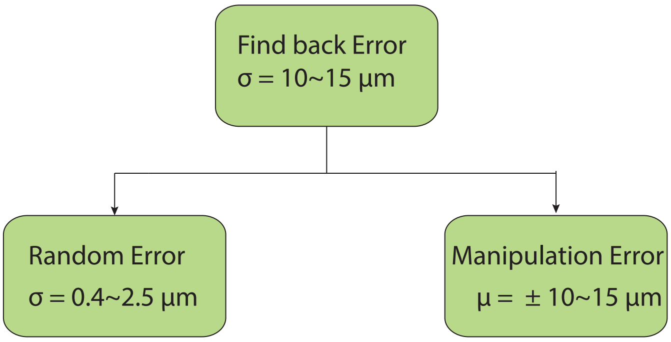
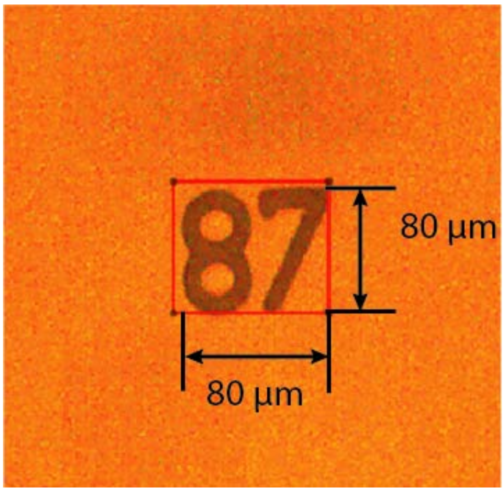
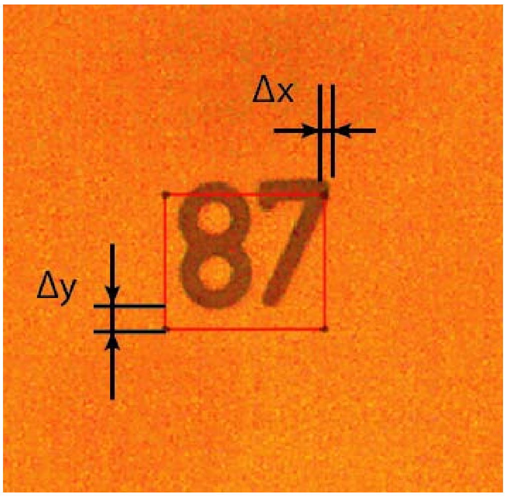


FIGURE 4.11: This figure shows the find back error. The manipulation error accounts for a large part of the whole find back error.

In Appendix D page 59 describes the procedure how to find back the interested cells. Calibration ruler is used to test the find back error. The height of the number '87' is 80 μm, as shown in Figure 4.12(A). The red rectangle is fixed on the screen. After finding back the same '87', the find back error is calculated by the distance between the red rectangle and the '87'. As shown in Figure 4.12 (B), the **find back error** is about± 10 to 15 μm in the x and y directions. The **manipulation error** caused by hand is $\pm$ 12 μm which is the main part in the whole find back error.



(A) The history coordinates (0.904, 1.924)mm



(B) The find back coordinates(0.916, 1.913)mm.

FIGURE 4.12: The original position (0.904,1.924) of '87' is within the red rectangle. Then the stage was moved to a random position. By moving the stage by hand to (0.916,1.913), the find error is 10 and 15 μm in x and y direction respectively.

It is concluded that the find back performance is limited by the manipulation error which is due to the manual error of the operator, limited accuracy and repeatability of the microscope stages. In the future, the stage can be precisely and actively positioned by an controllable actuator. Thus, the manipulation error can be dramatically reduced.

4.4.2 Results for Setup 2

This Due DAQ result is described in the same way as the NI DAQ result. The systematic error is the same as Section 4.4.1 NI DAQ result shown in Figure 4.9.

Find back error

As shown in Figure 4.13, the find back error consists of system random error and the user manipulation error. Compared with Figure 4.11, it is clear to see the random error of Due DAQ setup is almost 10 times bigger than in NI DAQ setup. The value of the random error is comparable with that of the manipulation error. The Due DAQ noise causes the main part in the random error.

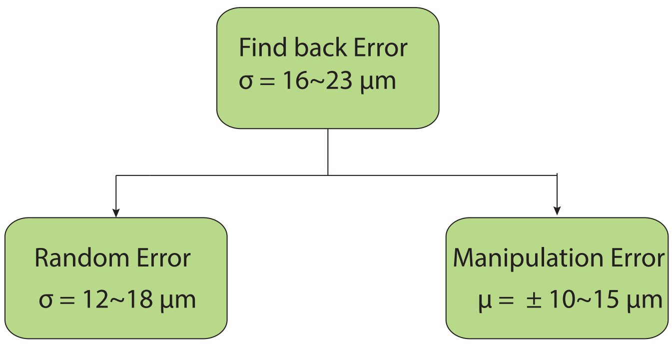


FIGURE 4.13: This figure shows the find back error of setup 2. The value of the random error is comparable with that of the manipulation error.

As a result, the Setup 2 with Due DAQ is sufficient to find back the normal plant cell, because this setup has 20 μm repeatability. The whole system can be made more compact by replacing the power supply of the sensor by a battery or a power block.

Chapter 5

Conclusions and recommendation

5.1 Conclusions

The 6-DoF measurement concept is developed, which can be integrated with the 6-DoF planar stage in the future. The measurement system is integrated on a microscope to help users to find back the interested objects (cells) under the microscope. The main conclusions of this thesis are as following:

1. The measurement concept is developed from a basic 2-DoF concept to 6-DoF concept step by step. The PSD settlement time is 10 μs which is fast enough to detect the light signal from the LEDs. By using the information from the five LEDs, the 6-DoF algorithm is easily deduced. (Chapter 2)

2. The pre-setup is tested the detection of x, y, z, θ_z. From the measurement result the conclusions are: Adding an external power supply (voltage supply noise level of 0.4 μm) to Arduino Uno achieves 6 time better result compared with only powered by a computer via the USB cable (noise level of 2.6 μm). Adding a light shielding can reduce the ambient light influence. Manufacturing and assembly errors are not relevant to the repeatability of the findback system. (Chapter 3)

3. In the microscope demonstration, two setups were built. The one with National Instrument DAQ shows that the system achieves a low noise level. The other one with Due DAQ proves the system is compact and at low cost. Table 5.1 and Table 5.2 show the system specifications achieved in the validation experiment.

TABLE 5.1: System Specifications of Setup 1 using National Instrument DAQ box

Specifications	Value
Measurement ranges	x: 9 mm y: 9 mm z: 3 mm
Degree of freedom	3
Accuracy	$\pm 20\mu m$ (x, y direction)
Random error(Repeatability)	$0.4 \sim 2.5\mu m$ $[\sigma]$
Find back error	$10 \sim 15\mu m$ $[\sigma]$
Measurement speed (eye reaction speed)	0.3s
cost	< 1800 euro

TABLE 5.2: System Specification of Setup 2 using Arduino Due DAQ

Specifications	Value
Measurement ranges	x: 9 mm y: 9 mm z: 3 mm
Degree of freedom	3
Accuracy	$\pm 20\mu m$ (x, y direction)
Random error (Repeatability)	$12 \sim 18\mu m$ $[\sigma]$
Find back error	$16 \sim 23\mu m$ $[\sigma]$
Measurement speed (eye reaction speed)	0.3s
cost	< 900 euro

In the above specifications, the find back error consists of system random error and the user manipulation error($\pm 10 \sim 15\mu m$). The conclusions are:

• If the users need to find back cells or microelectronics elements under a normal manually microscope, Setup 2 (cheaper) is recommended. Since finding back objects by manually microscope, these two setups don't make much difference (in same magnitude). As a result, the Setup 2 is good enough to find back the normal cells (diameter 80 μ m).

• If the users want to integrate a controller and an actuator in the whole find back system in the future, Setup 1 (lower noise level) is recommended. The find back performance of Setup 1 is limited by manipulation errors which are due to the manual error of the operator, limited accuracy and repeatability of the microscope stages. By an controllable actuator, the stage can be precisely and actively positioned. Thus the manipulation error can be dramatically reduced. The whole find back error will be about $0.4 \sim 2.5\mu m$. So this find back system can find back the objects on the micrometer scale, such as bacteria and comb-drives.

4. The cost list for Setup 1 and Setup 2 is shown in Table 5.3.

TABLE 5.3: The cost list for Setup 1 and Setup 2

Items	Price (Euro)	Setup 1	Setup 2	Alternative items
Duo-PSD	770	☑	☑	*
National instrument box-6211	860	☑		
Arduino Due	38	☑	☑	
± 15 V power supply	75	☑	☑	*
LED and printer materials	20	☑	☑	
Total cost		1763	903	

* The most of the expense is spent on the duo-PSD sensor. Another type of the 2D PSD is the tetra-lateral PSD which only costs 50 euro in Hamamatsu company[16]. If this type of PSD can be implemented in the system in the future, the cost can be reduced dramatically. In the datasheet, it is said the detection error is about 250 μm. If this error is caused by the non linearity of the sensor, this error will not influence find back application.

* The 15 Volt power supply can be replaced by battery (circuit with voltage regulator) or a 10 euro PCB power block [1] to reduce the whole system cost.

5.2 Recommendation

Below are some recommendations for the future work:

• *Accurate.* The 2D find back system investigated in this project doesn't need calibration. However, in other degrees of freedom detection, the accurate calibration is needed, since the x and y axes of sensor plane is not aligned with the x and y axes in the stage plane. Also, the manufacture and assembly error involve in the measurement. The planar calibration is required which is shown in Appendix B.

• *Fast.* The measurement concept introduced in the thesis is demonstrated in finding back an object on a microscope. At the end of each measuremetn loop, the pause

[1] The recommended power block is MYRRA -47247-DC ± 15 V which can be bought on the RS and Farnell webisite.

time is added for the users to response. For future close loop design, the pause time is not needed.

• *Compact and low-cost.* The ±15 Volt voltage supply occupies large space in whole system, battery (circuit with a voltage regulator) or a 10 euro PCB power block can take place of it. Buy one 50 euro tetra-lateral PSD and test the repeatability of the sensor to see if this can replace the 770 euro duo-PSD in the setup to find back the normal cells. It is possible to reduce the cost to about 200 euro to achieve 50 μm repeatability. the In the future, the PSD sensor and related circuit both can be integrated on the PCB board, such as Max Café 's 6 DoF ferrofluid stage actuator PCB board[1]. Furthermore, the PSD board and the LEDs box are manufactured in a closed structure, so the light shielding is not needed anymore.

• Some things need to take care of in experiment.
If you use Matlab and NI to do data acquisition, be sure to first insert NI cable into the PC then start the Matlab program. If you do it in the opposite sequence, the data acquisition will stop working.
Even though On the website of Ardunio said compared to Uno, the Due's DAQ has higher resolution 12 bit. You need to write code to set the analogread resolution to 12 bit, otherwise it works with 10 bit as default.

Appendix A

Component datasheet

This appendix shows the data sheet of position sensitive detector, LED, National instrument, Arduio Uno and Due.

A.1 Position sensitive detector

Table A.1: PSD $2L10-SU65-SPL01$ Specification

Characteristic	Typical
light wavelength	$400 \sim 1000nm$
active area	$10 \times 10mm^2$
position non-linearity	$\pm 0.3(0.8)\%$
input light power	0.025-0.3 mw
responsibility	$63V/mW$
resolution	2.5 μm
maximum output voltage	$\pm 12V$
output noise	$3mV_{p-p}$
3 dB bandwidth	400 KHz
slew rate	$13V/us$
supply current	12 (max 23) mA
detector resistance	$100K\Omega$
thermal drift	$40ppm/^{\circ}C$
internal bias on PSD	15 V

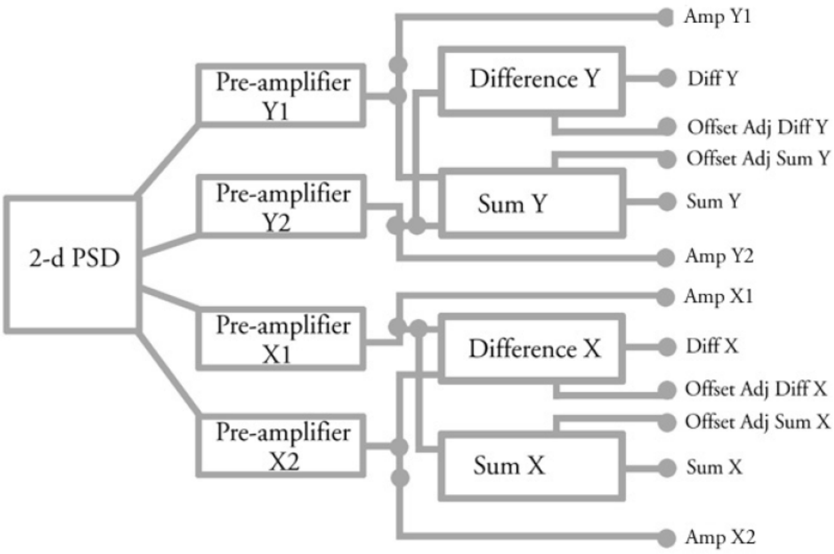


FIGURE A.1: Block schematics of the position sensitive detector amplify circuit

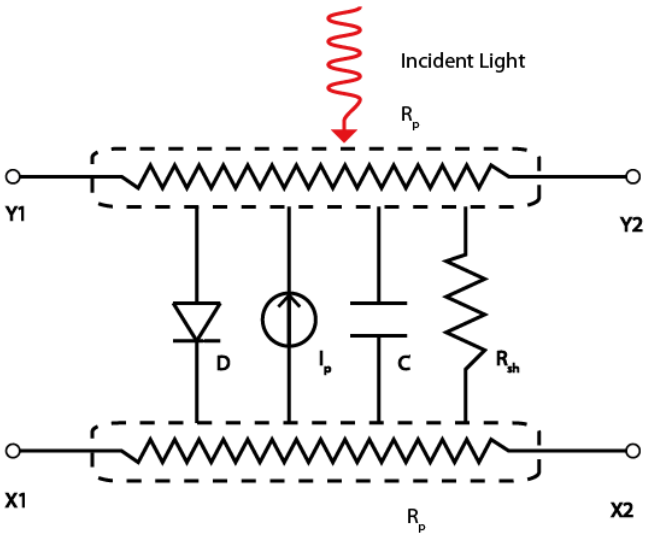


FIGURE A.2: The position sensitive detector equivalent circuit[3].

A.2 LED

Table A.2: LED Specification

Characteristic ($Ta = 25°$)	Typical
peak wavelength	635 nm
optical power@20mA	4.0 mW
viewing full angle	40°
revsese voltage	5 V (max)
forward current	50 mA (max)

A.3 National Instrument Box

Table A.3: NI comparison

Characteristic	NI 6211	NI 6008
Resolution	16 bits (0.3 mV)	12 bits(4.9 mV)
sample rate	250KS/s	10Ks/s
max voltage range	$-10V \sim +10V$	$-10V \sim +10V$
max voltage range accuracy	2.69 mV	138 mV
max voltage range sensitivity	91.6 uV	
mini voltage range	$-200 \sim +200mV$	$-1 \sim +1V$
mini voltage range accuracy	0.088 mV	37.5 mV
mini voltage range sensitivity	4.8 μV	
price	860 Euro	175 Euro

A.4 Arduino Uno and Due

Arduino Uno and Due comparison In the chapter 3, the Uno is used in controlling the LEDs on and off. Due is applied in Chapter 4 because I want to use Due to control LEDs and and also do the data acquisition.
Due has two main advantages in this application:
1.**High ADC resolution**
Compared to Uno, the Due's DAQ has higher resolution 12 bit.
2.**Stable voltage output**.
When the Arduino is powered by PC via USB, Due V_{pin} is measured with the uncertainty of 0.4 mV (3.6 p-p mV), while Uno is measured with the uncertainty of 2.3 mV (10.1

Table A.4: Arduino Uno and Due comparison

Characteristic	Uno	Due
ADC Resolution	10 bits	12 bits
operating voltage	5 V	3.3 V
Input voltage via USB connection	5 V	5 V
Input voltage via VIN pin	7 to 12 V	7 to 12 V
DC current per I/O pin	40 mA	15 mA
DC current for 3.3 Vpin	50 mA	800 mA
Price(On RS website)	21 euro	38 euro

p-p mV). Chapter 3 already shows when Uno powered by voltage supply can achieve uncertainty of 0.38 mV (3 mV) this result is comparable with the Due only powered by PC. Because Due has the on board regulator to stabilize the voltage from the computer.

Transistor switch circuit

The chapter 3 shows the LEDs is in series with resistors connected to the Arduino uno digital pin. In Chapter 4, the Arduino Due is used. While the Due digital pin can only provides 15 mA current which is not enough for powering the LEDs. So the following transistor switch circuit is made. The digital pin only has the switch function. The LED is powered by the 3.3 V_{pin}(800 mA limit)on Due board. The center resistor which is in series with central LED2 is 15 Ω. The others are 6.2 Ω. Because if connecting the LEDs with same resistors, the power come out of the pinhole from LED1 and LED3 is half value of from center LED2.

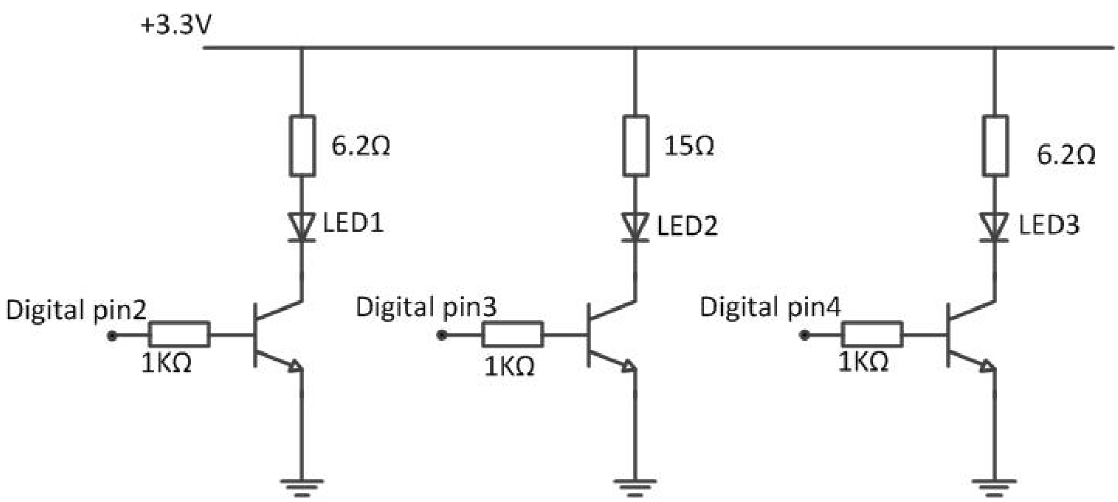


Figure A.3: The drawing of the switch circuit shown in Figure 4.5 in Chapter4.

Appendix B

Recommended algorithm for calibration x and y

The planar calibration is not needed in the x y directions microscope find back system described in Chapter 4. Because find back objects based on how good the repeatability of the system. However, in other degree of freedom detection, the accurate calibration is needed.

In reality, the x and y axis of sensor plane and the stage plane is not align. The calibration of the plane is required. The following algorithm is used for transform the point P from (x, y) on stage coordinates to the (x', y')on sensor coordinates. The relationship between (x, y) and (x', y') can be put into a matrix form. After the planar calibration, from each sensor output coordinates, the real value of the stage can be deduced.

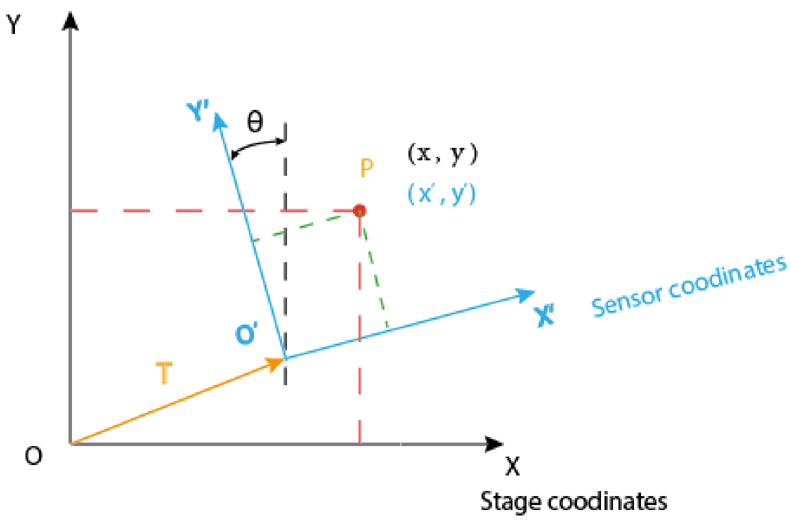


FIGURE B.1: transform relation between the sensor coordinates and stage coordinates

$$\begin{bmatrix} x \\ y \end{bmatrix} = \begin{bmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{bmatrix} \cdot \begin{bmatrix} x' \\ y' \end{bmatrix} + \begin{bmatrix} T_x \\ T_y \end{bmatrix}$$

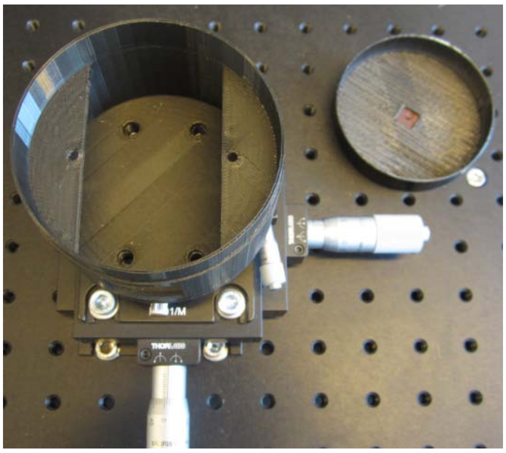
Appendix C

Microscope demonstration designed details

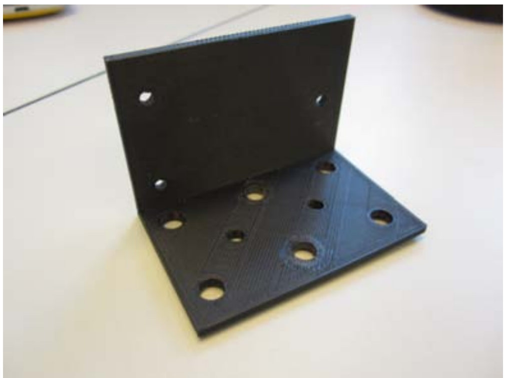
C.1 Components design details

Pre-setup 3D components

Figure C.1shows the 3D components printed in Chapter 3 pre-setup.



(A) The pre-setup described in Chapter 3

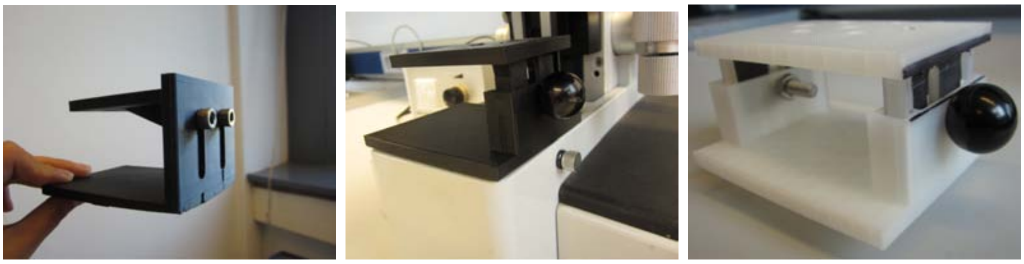


(B) The right angle connector

Figure C.1: (A) figure shows the 3D components used in Chapter 3 pre-setup.(B)The right angle connector fixed the PSD sensor with the pillars which can adjust height along construction rail.

The height adjustment

The height adjustment has three developed editions as shown in Figure C.2. The first height adjustment edition is designed with two slips, while the users have to align the two connectors and fasten the two screws. In order to make it user friendly, the guider design is added in the second edition. The users only need insert connector 2 into connector 1 and adjust the height by one screw. After mounting all the components, the bending effect is detected causing by this cantilever design. Using one guider is not stable. Thus, the third one with two guiders comes out.



(A) The first height adjustment edition

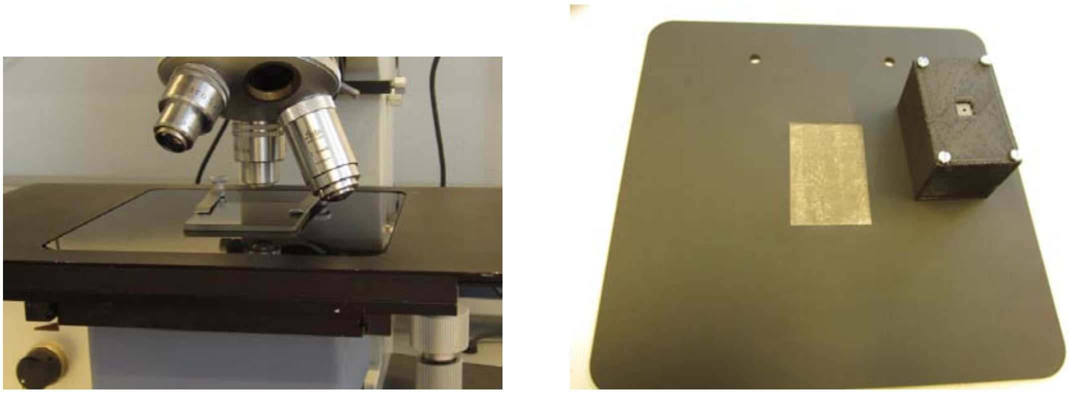
(B) The second height adjustment edition

(C) The third height adjustment edition

FIGURE C.2: (A)The first height adjustment edition(B)The second height adjustment edition.(C)The third height adjustment edition

The bottom connector has a cylinder designed at its underside, which can insert into the round hole on the microscope. One thing need to keep in mind is that click the "support" button on the 3D printers software before printing this component. Otherwise this whole components will break down.

The objective stage



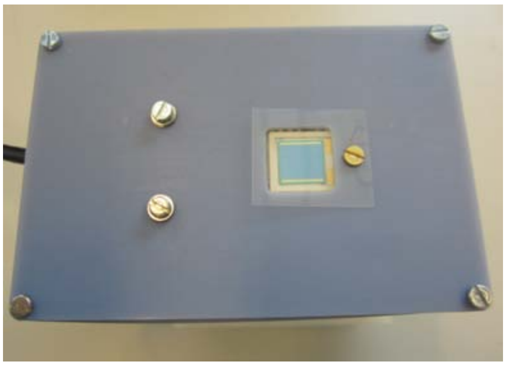
(A) The objective stage

(B) The bottom view of objective stage

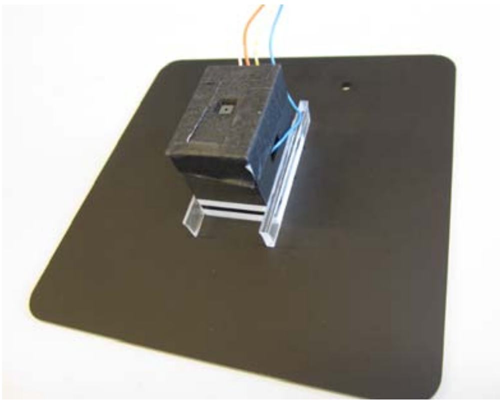
FIGURE C.3: (A) figure shows the laser-cutting Objective stage.(B)figure shows the bottom view of objective stage.

The acrylic objective plate is designed as the same size as the original microscope glass plate. I designed two holes at the top of the plate which can insert stage clips to fix the object on the stage shown in Figure C.3. The same area as the LED box is engraved to white color at the back side of the plate. Glue the LED box to the bottom surface of stage, when white engrave area is totally covered by the black LED box. Thus, the engraved area helps the users align the LED box to stage effectively.

The sensor box and LED box



(A) The PSD sensor box



(B) The LEDs box

FIGURE C.4: (A) figure shows the laser-cutting Objective stage.(B)figure shows the bottom view of objective stage.

A dust cap is added on the PSD sensor box to keep the dust away shown in Figure C.4. The users can rotate the cap around the screw when they want to open or close it.
The black an white plates cut by laser can be added between LED box and objective plate, in order to adapted to different microscope. Using black and white color (large color difference)can reduce the difficulty of alignment.

C.2 The noise level of PSD center and boundary

The noise level at the sensor boundary (2.5 μm) is 6 times larger than in the center (0.4 μm) shown in Figure C.5. This indicates the PSD noise level given by company is taken near the PSD center.

The result is measured by National Instrument box with 0.1 and 1 s sampling time respectively. The conclusions are:
• The noise level at sensor boundary (2.5 μm)is 6 times larger than the center (0.4 μm)[12].(shown in Figure C.5)
• Increasing sampling time from 0.1 s to 1 s, the big noise contribution of low frequency (smaller than 10 Hz) can be seen in sensor boundary cumulative power spectrum Figure C.7.
• The low frequency influences the sensor output voltage when PSD at the boundary

more than in its center. This could be caused by the sensor silicon diode's Physics property.(Compare the Figure C.6 and C.8)

• Compared Figure C.5 and C.7, even though the noise level of the sensor voltage output pin is increased from 0.41 mV to 10.7 mV , the sensor readout x noise level is not change(2.5 μm) because of the quotient calculation introduced in Section 2.1.1.

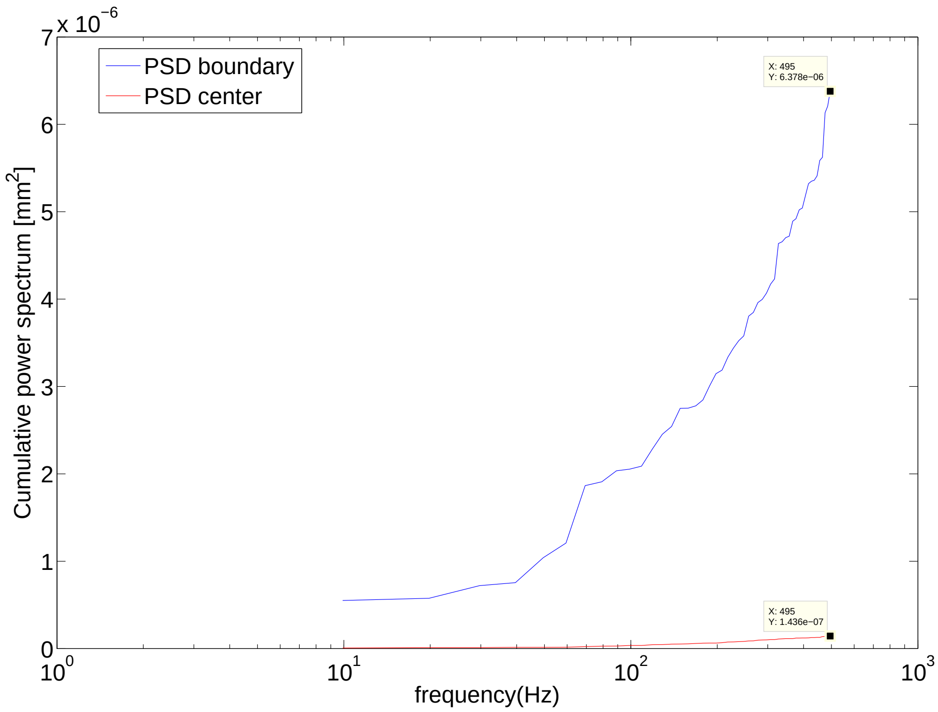


FIGURE C.5: $Samplingtime = 0.1s$. Sampling time=0.1 s. This cumulative power spectrum shows the difference noise level of sensor output x position when detect PSD center (0.4 μm) and boundary (2.5 μm)

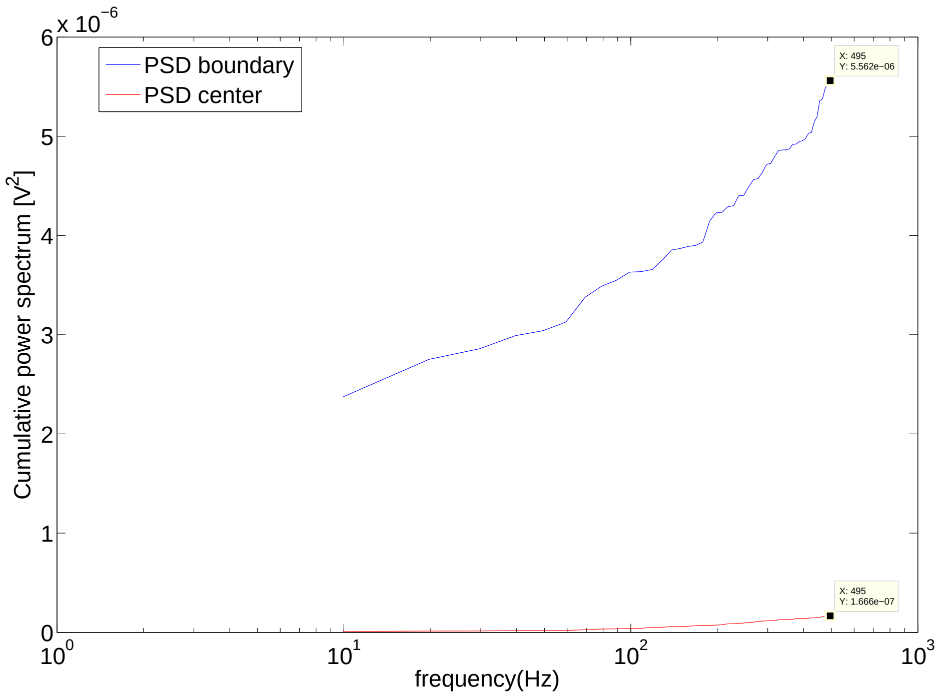


FIGURE C.6: $Samplingtime = 0.1s$. This cumulative power spectrum shows the difference noise level of sensor output voltage(Sum X) when detect PSD center(0.4 mV) and boundary (2.4 mV)

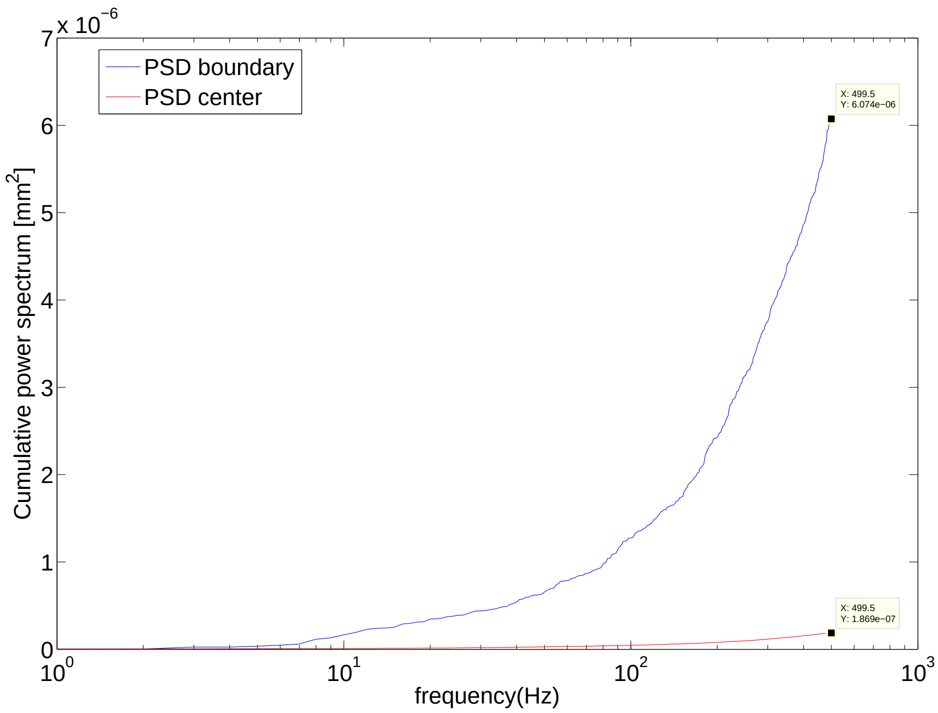


FIGURE C.7: $Samplingtime = 1s$. This cumulative power spectrum shows the difference noise level of sensor output x position when detect PSD center (0.4 μm) and boundary(2.5 μm).

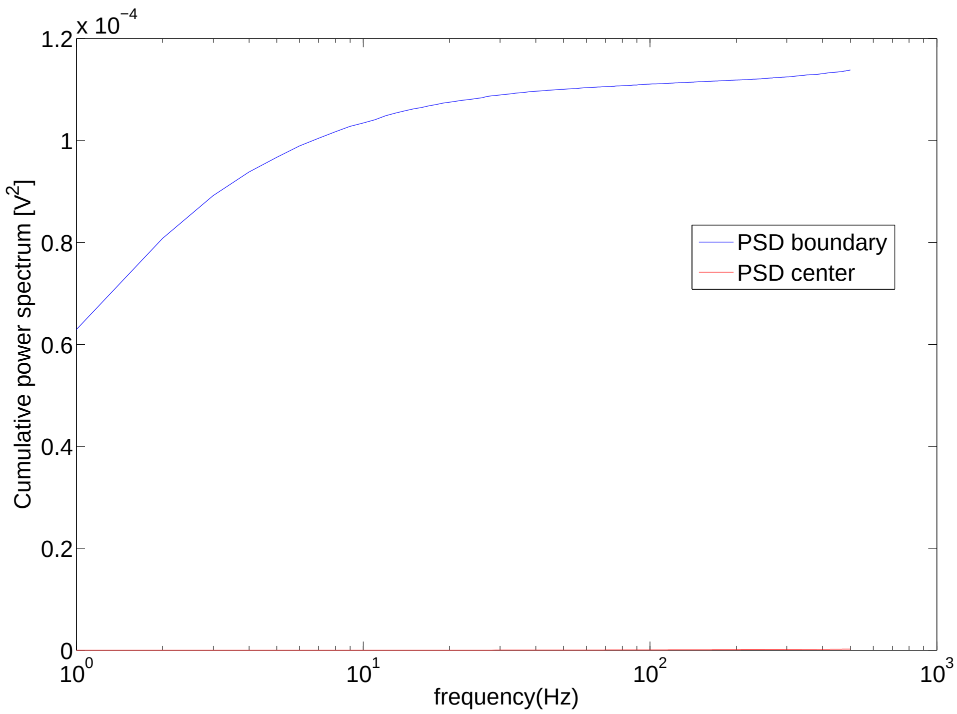


FIGURE C.8: $Samplingtime = 1s$. This cumulative power spectrum shows the difference noise level of sensor output x position when detect PSD center (0.5 mV) and boundary (10.7 mV).

Appendix D

Advertisement leaflet and user handbook for ”Observer”

D.1 Advertisement leaflet- "Observer"

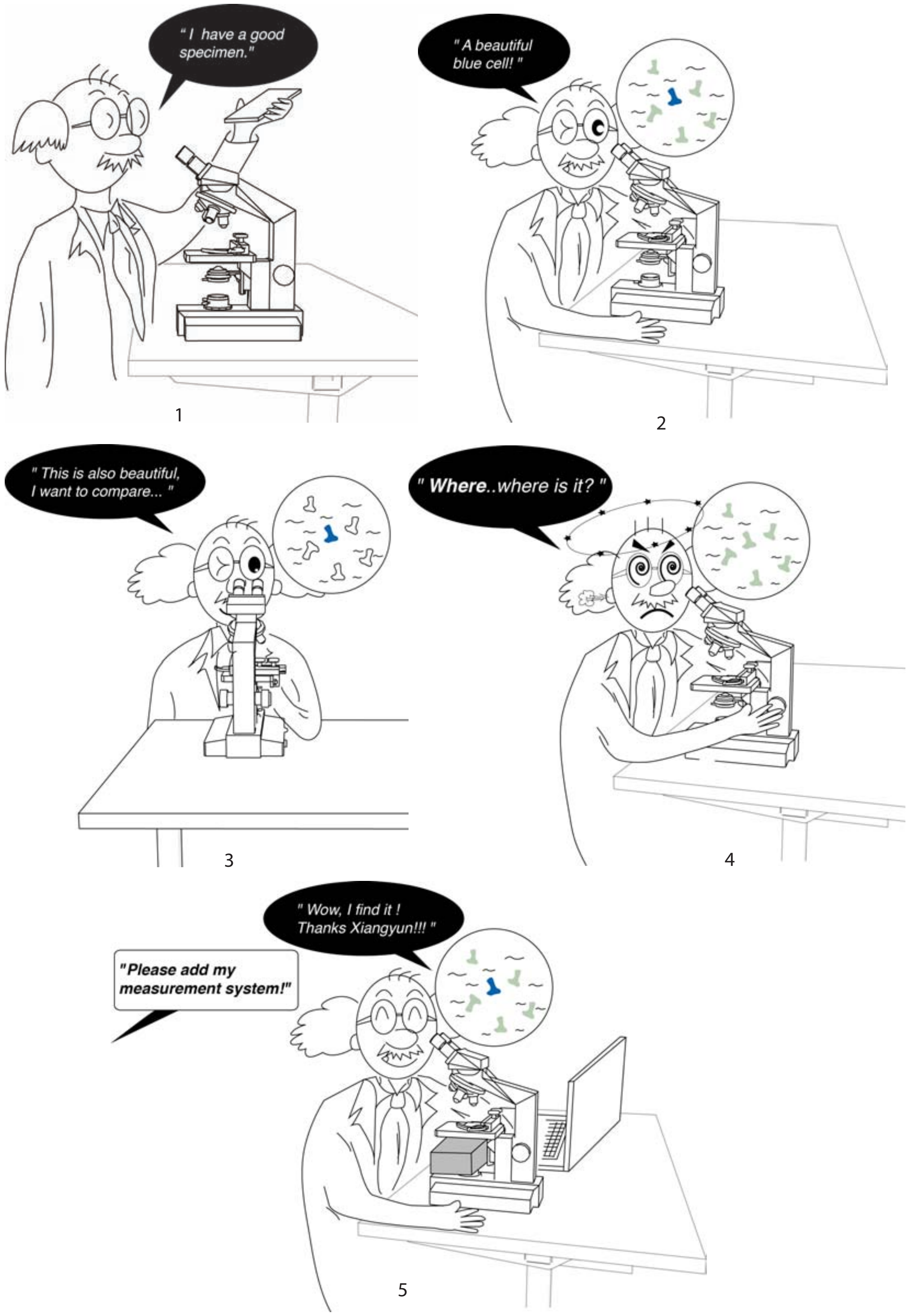


Figure D.1: The advertisement for my sensor system.

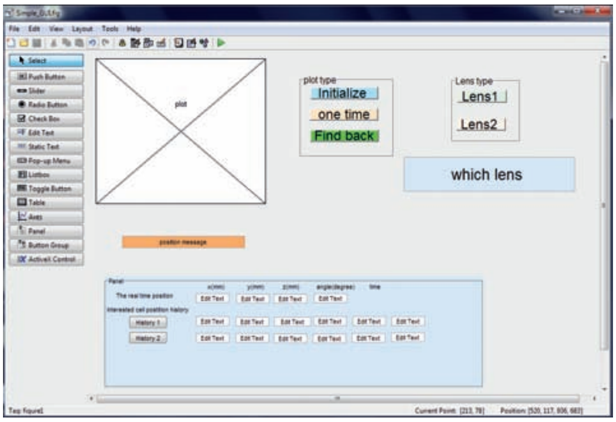
D.2 User hand book for "Observer"

The component list Figure 4.3 and mounting procedure Figure 4.2 have already be shown in the chapter 4.Here will illustrate the finding back procedure.

FIGURE D.2: whole microscope find back system

1 Open the GUI software.

Click Initialize



2 How to adjust the lens in focus?

Here choose the lens 2 as the example

1. Click the push botton Lens2

2. Then adjust the height of the microscope stage based on the message of

Lens 2 is out of focus

Lens 2 is in focus

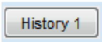
Danger!Danger!

This message reminds users the lens will touch the specimen.

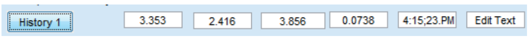
FIGURE D.3: How to adjust the lens to the focus point

3 How to find back cells?

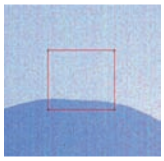
1. When you find the interested cell under your objective lens

click pushbotton 

, the coocinates (x, y, z, θ) will be shown in the following history table. The time the user took the measurement will be also displayed in the table. The users can type some notes when he observing the interested objective.

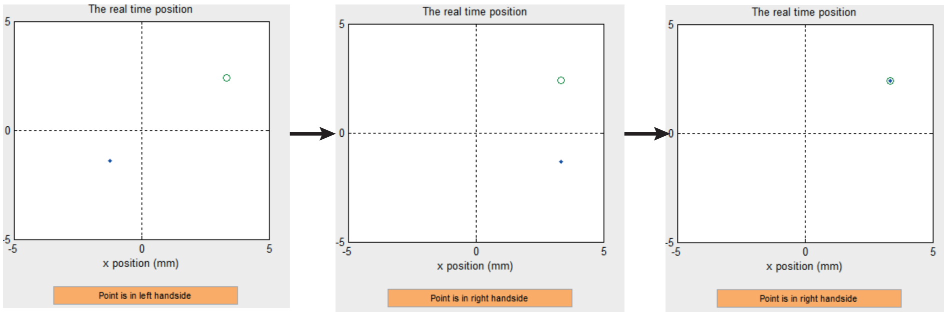


2. Keep on moving the stage to observe other part of the specimen.



3. Start to find back. Click the push botton 

The plot window will remind the user where is the stage now using the ' . ' marker, using the circle ' o ' to represent the history point. Then the user's work is to move the point in the circle.



The users will see the interested objective again under the microcope.

4 Measure the size of the interested cell.

Users should use crosshair in the microscope eyepiece as the reference. (or use the refercence on their camera screen). Do one time measurement on the left side of the objective, then do one time measurement on the right side the objective . Calculate the length by the x coodinates.

FIGURE D.4: How to find back the interested cell

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