

DIEAGNOSIS

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Design Document for ECE 445, Senior Design, Fall 2026

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02 October 2026

Project No. 9

Table of Contents

1. Introduction	1
1.1 Problem	1
1.2 Solution	1
1.3 Visual Aid	2
1.4 High-Level Requirements List	2
2. Design	3
2.1 Block Diagram	3
2.2 Physical Design	4
2.3 Subsystem Overview	5
2.3.1 Optical Sensing	5
2.3.2 Wafer Motion and Positioning	6
2.3.3 Data Acquisition and Control	9
2.3.4 Data Processing and Wafer Mapping	11
2.3.5 Enclosure	11
2.3.6 Power	12
2.4 Tolerance Analysis	14
3. Cost and Schedule	17
3.1 Cost Analysis	17
3.1.1 Labor	17
3.1.2 Parts	17
3.1.3 Sum of Total Cost	18
3.2 Schedule	19
4. Ethics, Safety and Societal Impact	20
4.1 Societal Impact	20
4.2 Engineering Standards	20
4.3 Ethics	20
4.4 Electrical Safety	21
4.5 Mechanical Safety	21
4.6 Laser Safety	21
4.7 Safety Mitigation Procedures	22
5. References	23

1. Introduction

1.1 Problem

In ECE 444, wafers are inspected under a microscope after fabrication steps to make sure the process was completed correctly. Since a wafer can contain dozens of dies and hundreds of devices, it is not practical to inspect every device after every fabrication step. Instead, only a small number of locations are usually inspected, and the rest of the wafer is assumed to be similar.

This can make it difficult to determine why a device fails after fabrication. For example, a problem with photoresist removal, etching, or deposition may affect a region of the wafer without being noticed during manual inspection. If the problem is only discovered during electrical testing, it can be difficult to determine which fabrication step caused it.

A missed fabrication problem can also affect later processing steps. In ECE 444, for example, wafers are sometimes moved between processes where contamination from an earlier step can affect subsequent fabrication. Photoresist removal is particularly important before furnace processing because leftover photoresist will contaminate the furnace and ruin the wafer. This makes it useful to know not only whether a wafer has a problem, but also where the problem is located before continuing with the fabrication process.

1.2 Solution

An automated inspection system could scan a much larger portion of the wafer after each fabrication step and identify regions that differ from the expected surface condition. This would provide additional information about where a fabrication problem may have occurred without requiring manual inspection of the entire wafer.

The proposed system will use a laser and photodiode to measure the optical response of different locations on the wafer. The wafer will be mounted on a moving X-Y stage while the laser and photodiode remain fixed to achieve a raster scan. The photodiode measurements will be collected by a microcontroller along with the corresponding X-Y positions. The measurements will then be sent to a computer, where they will be compared against a baseline measurement from an ideal wafer and displayed as a two-dimensional map. The system will be enclosed to reduce ambient lighting.

The intended use of the system is to place a wafer into the inspection system after a fabrication step and automatically scan the wafer before continuing to the next step. For example, after photoresist removal, the system could scan the wafer to identify regions that have an optical response different from the expected wafer surface before the wafer is placed into a furnace. The system would not determine the exact cause of a defect, but it could identify where on the wafer further inspection is needed. This could allow users to inspect specific regions instead of relying only on a small number of manually selected locations.

1.3 Visual Aid

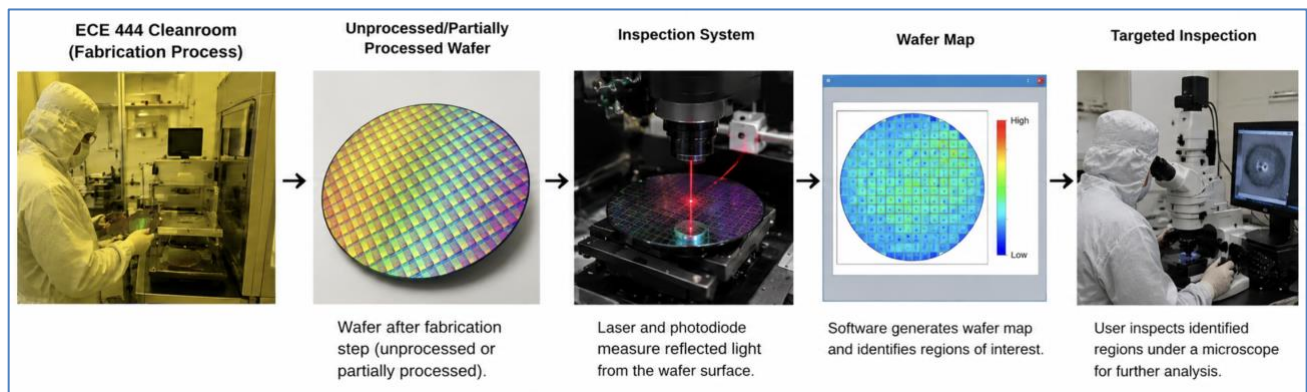


Figure 1: Diagram of the Proposed System Flow

1.4 High-Level Requirements List

Optical Measurement Repeatability and Anomaly Detection. The system should produce repeatable optical measurements at a fixed wafer location under identical operating conditions, with consecutive measurements varying by no more than 10% from the mean of the measurements. The system should be able to detect and distinguish between a baseline wafer and a wafer with an intentionally introduced defect (photoresist, dust, large scratches) in more than 90% of tests. A detection is considered successful if the corresponding wafer map highlights the correct coordinate for further inspection. This demonstrates that the system can identify meaningful surface abnormalities rather than only measure random variations.

Wafer Positioning and Spatial Mapping. The system should automatically position a 4-inch wafer across an X-Y raster scan with a positioning discrepancy of no more than ± 0.25 mm. The stage should return the wafer to a designated origin position after a complete scan. The system should record the X-Y coordinates associated with each optical measurement and generate a two-dimensional map of the scanned region on a computer, allowing each detected optical anomaly to be associated with its corresponding physical location on the wafer. The difference in the physical position of the wafer and what is recorded on the computer should not differ by more than ± 1 mm.

Ambient Light Isolation. With the system enclosure installed, the photodiode measurement should remain stable despite changes in ambient lighting conditions. When exposed to ambient light levels (ECEB 2070 lighting), the measured photodiode signal should vary by no more than 10% relative to the measurement obtained under the baseline lighting condition. This requirement ensures that the optical measurements are determined by the wafer surface and inspection system rather than external lighting.

2. Design

2.1 Block Diagram

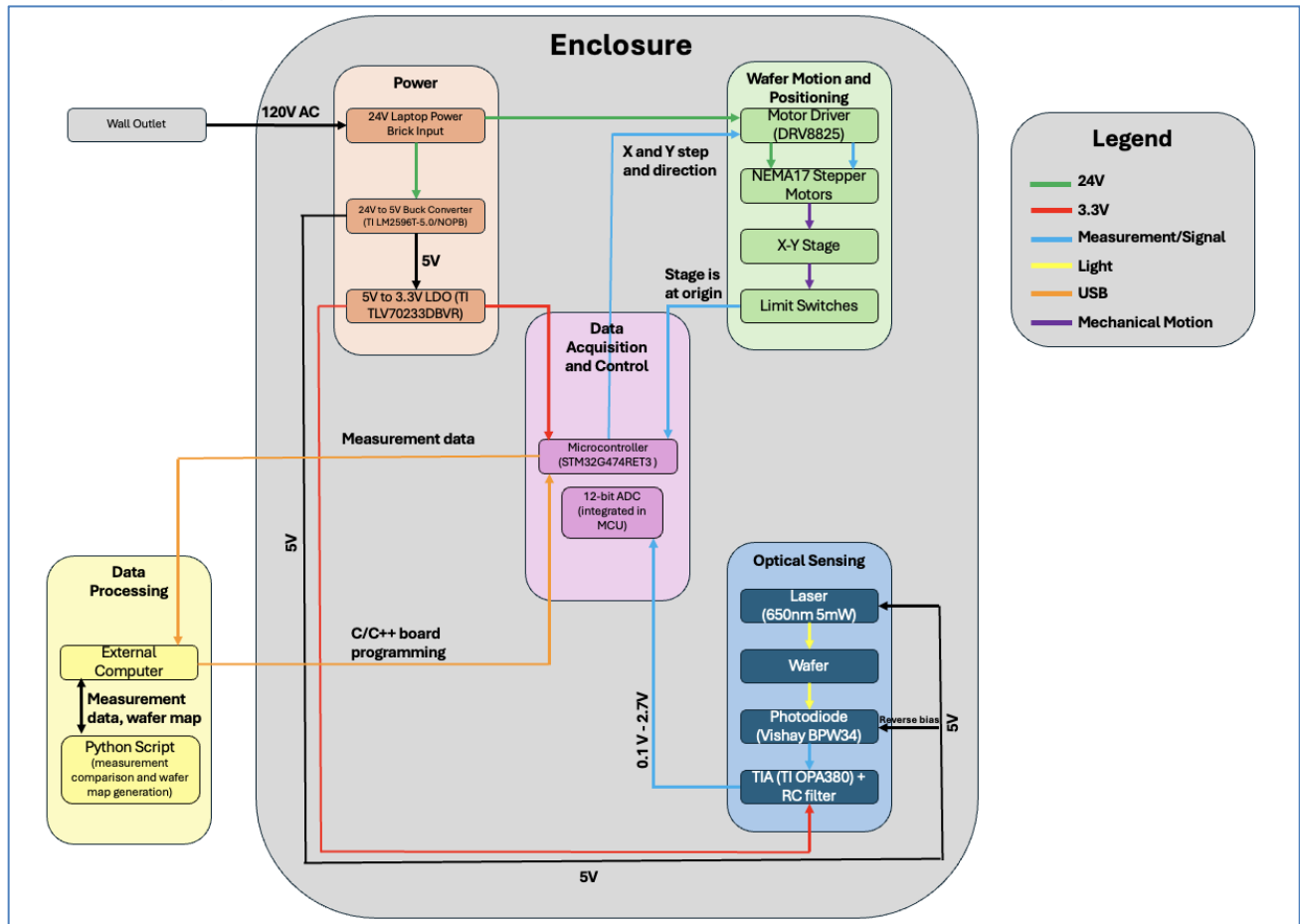


Figure 2.1: Block Diagram of the Proposed System

2.2 Physical Design

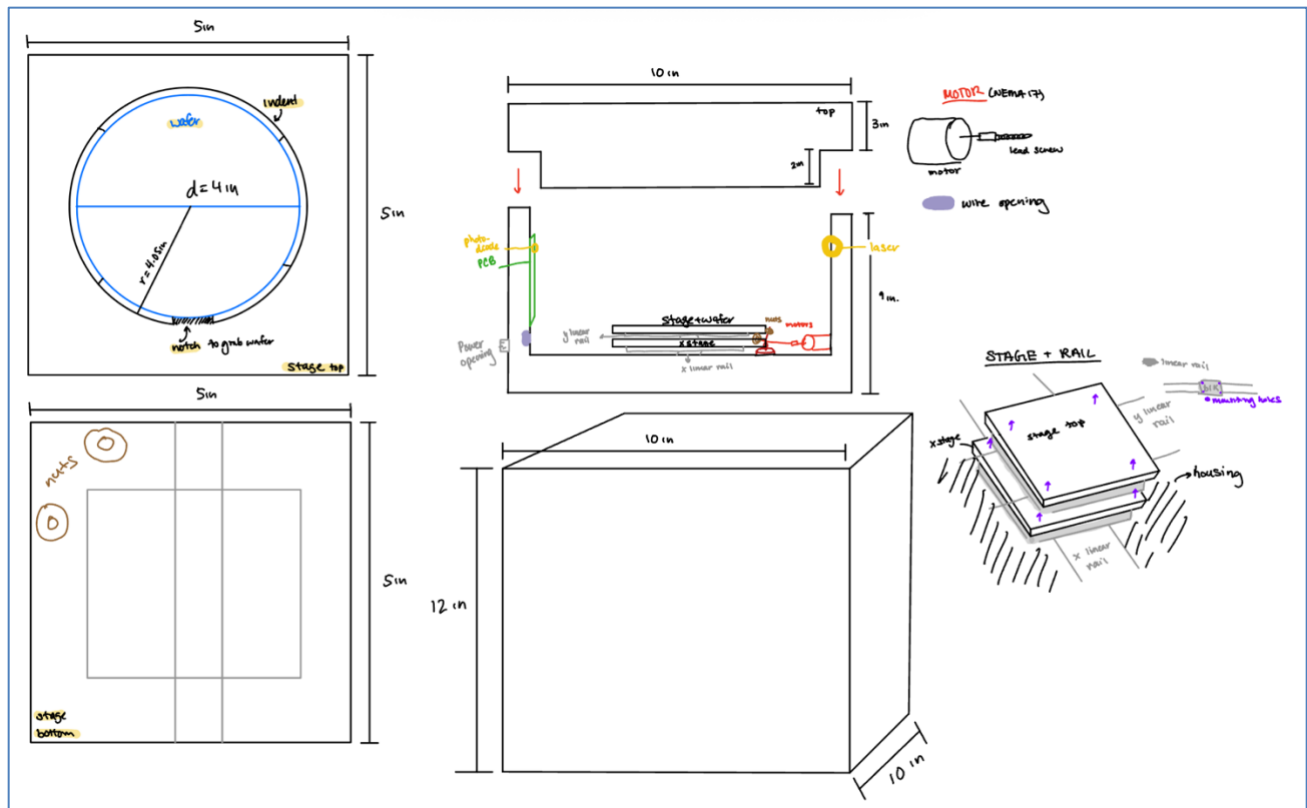


Figure 2.2: Physical Design Configuration

Figure 2.2 outlines the physical design of our housing, stage, and the positioning of our PCB and laser. The top left is the top of the stage where the wafer will sit. In the picture we see that on the top side of the stage will be a circular indent and a notch at the bottom so that the user can easily place the wafer onto and take out of the stage and so the wafer doesn't move around on the stage. Below that in the bottom left is the underside of the stage the wafer goes on where there is one linear rail that will allow the stage to move freely. Also on the underside are two nuts aligned in the x and y direction that are fastened to the stage for the stepper motors to move. Moving to the middle of Figure 2.2, the top middle drawing is what the inside of our housing will look like. Our housing will use a lap joint to prevent any ambient light from affecting our measurements. Inside, we will position our PCB and lasers on opposite vertical faces of the inside of our housing. Along the inside of the housing, there will be a hole drilled so that we are able to power our PCB using a wall outlet for our power subsystem. At the bottom of the inside of the housing there will be our stage that's sitting on a linear rail that is sitting on another stage that sits on a final linear rail perpendicular to the first one that is fastened to the housing. The two nuts that were mentioned in the bottom left can be seen to be on the underside of that stage with the wafer that have been threaded by the lead screws connected to our NEMA 17 motors in red. The bottom middle figure can be seen what the housing will look like once the lid is put on to create a rectangular prism. Finally, the drawings on the right show in more detail what the motors and stages with rails look like. The top drawing shows that we will fit a coupler onto the stepper motor and then fit the lead screw to that to screw into the nut to shift the stages forward and backward. The bottom right drawing shows an isometric view of the stage with rails where we will screw each of the rails to be secured to the stages and the bottom rail will also be secured to the housing allowing our stage to move freely as the motors drive the stage's motion.

2.3 Subsystem Overview

2.3.1 Optical Sensing

The optical sensing subsystem measures changes in the wafer's reflected and scattered light as the wafer is scanned. A 650 nm 5 mW laser illuminates the wafer with a spot size no larger than 2 mm. The system may use a focusing lens if we determine that our raw laser spot size is too large during prototyping. The laser and photodiode remain fixed while the X-Y stage moves the wafer. The 650 nm wavelength was selected over 405 nm and 532 nm because it provides adequate BPW34 sensitivity while remaining inexpensive and readily available.

A Vishay BPW34 photodiode converts the detected optical power into photocurrent. The BPW34 can operate with reverse bias, and its datasheet specifies a minimum of 40 μA and an average of 50 μA of reverse light current under a particular 950 nm test condition at 5 V reverse bias. This confirms that photocurrents in the tens of microamps are within the useful range of the device, although the actual current in this system will depend on the 650 nm optical geometry and wafer reflectivity. The photocurrent is converted to a voltage by an OPA380 transimpedance amplifier according to $V_{TIA} = I_{PD} \cdot R_F$, where I_{PD} is the photodiode current and R_F is the feedback resistance.

A feedback resistance can therefore be selected to place the expected TIA output within the voltage range required by the ADC. The STM32G474RET3 ADC has an output swing of 0.6V from V_{DD} and 0.1V from V_{SS} , so a supply voltage of 3.3V yields an output range of 0.1V to 2.7V. The final value for the feedback resistance will be determined from measurements gathered from the prototype optical system, but more analysis is provided in the Tolerance Analysis. An RC low-pass filter after the TIA will reduce high-frequency noise before the signal reaches the STM32 ADC.

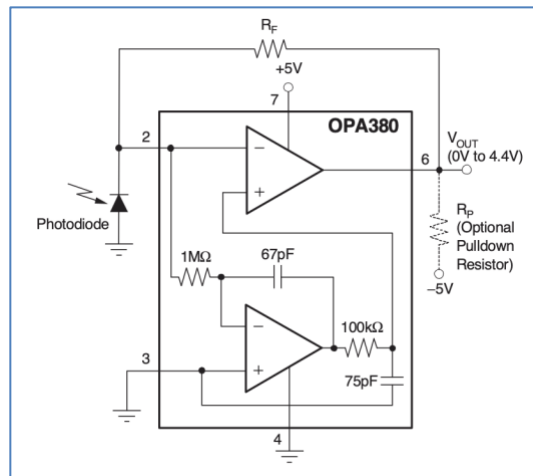


Figure 2.3.1: Typical OPA380 TIA Operation

Requirements	Verification
The optical subsystem should produce a laser spot with a diameter of ≤ 2.0 mm at the wafer surface.	Shine the laser at a wafer at the operating distance and angle. Use a ruler to measure the laser spot at the wafer surface. Verify it is ≤ 2.0 mm.
Consecutive optical measurements at the same wafer location should remain within $\pm 10\%$ of their average value under identical conditions.	Place a wafer at a fixed location and collect at least 10 consecutive measurements without moving the wafer or optical components. Calculate the mean

	and percent deviation of each measurement from the mean. Verify no measure has greater than a 10% deviation from the mean.
The conditioned photodiode signal should remain within 0.1V to 2.7V when inspecting a wafer.	Measure the TIA output with a DMM while scanning different wafer surfaces. Scan an unmodified wafer, a wafer with a sharpie dot, a wafer with a photoresist spot, and a wafer with a large scratch. Verify the output remains within the specified range for all tests.
The system should correctly distinguish a baseline wafer surface from an intentionally introduced optical anomaly in at least 90% of tests.	Scan a baseline wafer and wafers with intentionally introduced anomalies at known locations. Repeat the test for at least 10 trials and verify that the wafer map correctly identifies the anomaly location in at least 90% of trials.

2.3.2 Wafer Motion and Positioning

The motion subsystem moves the wafer through a predefined scan pattern so that an optical measurement can be collected at each predetermined location on the wafer. The wafer has a diameter of 4 inches, or 101.6 mm. The motion subsystem scans the usable portion of the wafer using 2 mm × 2 mm measurement regions with measurement centers spaced 2 mm apart. The scan is limited to locations where the entire measurement region remains within the wafer boundary, preventing measurements from being collected from the stage outside of the wafer. This subsystem provides accurate and repeatable positioning of the wafer relative to the fixed laser and photodiode while minimizing movement during each optical measurement.

The usable measurement area is determined from the geometry of the wafer and the measurement region. The wafer is modeled as a circle with radius

$$r = \frac{101.6}{2} = 50.8 \text{ mm.}$$

Because each measurement represents a 2 mm × 2 mm square, the center of the square must remain far enough from the wafer edge for all four corners to remain within the wafer. The distance from the center of the measurement square to one of its corners is

$$\sqrt{1^2 + 1^2} = \sqrt{2} \text{ mm.}$$

Therefore, the effective radius within which measurement centers can be located is

$$r_{\text{eff}} = 50.8 - \sqrt{2} = 49.386 \text{ mm.}$$

The corresponding usable area is

$$A_{\text{usable}} = \pi r_{\text{eff}}^2 = \pi(49.386)^2 \approx 7662 \text{ mm}^2.$$

Since each measurement location represents a 2 mm × 2 mm region, the approximate number of possible measurement locations is

$$N \approx \frac{7662}{2 \times 2} \approx 1915.$$

Thus, approximately 1,915 measurement locations are available on a 4-inch wafer. The circle equation is used by the control algorithm to determine which grid locations fall within this usable measurement region.

For homing, the scan begins by establishing a known reference position using mechanical limit switches. A limit switch is located at the home position of each axis. The stepper motors move toward their respective switches until they are activated. Once both switches have been triggered, the STM32G474RET3 sets the corresponding X and Y positions as the home position and begins the scan.

The measurement centers are separated by 2 mm in both the X and Y directions. At each measurement location, the motors move the wafer to the required position and then stop before the optical measurement is collected. A settling period is included after the motors stop to reduce the effects of mechanical vibration on the laser and photodiode measurements. The measurement sequence therefore consists of moving to a location, stopping the motors, allowing the stage to settle, and collecting the optical measurement.

The center of the wafer is defined as the coordinate origin, so the wafer boundary is described by

$$x^2 + y^2 = (50.8)^2.$$

The usable measurement region is similarly described by

$$x^2 + y^2 \leq (49.386)^2.$$

For the upper-left portion of the usable region, the first measurement center lies along the line $x = -y$. Therefore,

$$x^2 + (-x)^2 = (49.386)^2,$$

giving

$$x = -34.921 \text{ mm}, y = 34.921 \text{ mm}.$$

The STM32G474RET3 uses the effective-radius circle equation to determine whether each potential measurement location is within the usable wafer region. If the next 2 mm measurement location is valid, the X-axis moves to that location, and the optical measurement is collected. Once the next location in the current row falls outside the usable region, the stage moves down 2 mm in the Y direction and reverses the X-axis direction. This creates a zigzag scanning pattern and avoids unnecessary return movements between rows. The scan continues until all valid measurement locations within the usable region have been measured.

We selected the 17HS15-1704S NEMA 17 stepper motor because it has a 1.8° step angle, corresponding to

$$\frac{1.8^\circ}{360^\circ} = \frac{1}{200} \text{ revolution/step.}$$

Using the selected lead screw and coupler, one motor revolution produces 8 mm of linear stage movement. Therefore, one full motor step produces

$$\frac{8 \text{ mm}}{200} = 0.04 \text{ mm/step,}$$

or 25 full steps per millimeter of stage movement. This provides sufficient resolution to command the required 2 mm spacing between measurement centers. With 1/16 microstepping, the theoretical commanded increment is

$$\frac{0.04}{16} = 0.0025 \text{ mm}$$

per microstep. Microstepping also provides smoother motor motion and can reduce vibration during positioning. The NEMA 17 motors were selected because they provide controlled and repeatable motion while remaining relatively inexpensive and compatible with the custom X-Y stage.

The TI DRV8825 motor driver was selected because it can operate from the project's 24 V power supply and provides regulated current control for the bipolar NEMA 17 motors. One DRV8825 is used for each axis and provides the two H-bridges required to control the two windings of its corresponding stepper motor. The drivers also provide the selected 1/16 microstepping capability. The STM32G474RET3 interfaces with each DRV8825 through step and direction control signals, while the drivers control the current supplied to the motor windings.

Mechanical limit switches provide a low-cost reference position for the X and Y axes before each wafer scan. A custom X-Y motorized stage provides linear motion in both axes, with the stepper motors driving the axes through lead screws. A custom 4-inch wafer holder secures the wafer during scanning and prevents movement that could affect optical measurements while keeping the wafer surface accessible to the laser and photodiode. Together, the X-Y stage, stepper motors, lead screws, limit switches, and wafer holder provide the positioning and stability required for the scan.

The motion subsystem interfaces with the control subsystem through the STM32G474RET3. The STM32 sends step and direction signals to the two DRV8825 drivers and receives digital signals from the X and Y limit switches. Each motor produces 25 full steps per millimeter of stage movement, allowing the controller to accurately command the 2 mm spacing between measurement centers. The motion subsystem also interfaces with the optical measurement subsystem. The STM32 commands the stage to stop at each measurement location and initiates optical measurement only after the programmed settling time has elapsed. This ensures that optical measurements are collected while the wafer is stationary.

Requirements	Verification
The motion subsystem should position the wafer at measurement locations with 2 mm spacing.	Command the stage to move 2 mm and measure the actual displacement using a caliper or other position

	measurement tool. Repeat the test at least 5 times and verify that the measured displacement is within ± 0.25 mm of the commanded 2 mm.
The homing procedure should establish a repeatable reference position within ± 0.10 mm.	Home each axis 10 consecutive times and measure the resulting position relative to a fixed reference mark. Verify that the maximum difference between the origin and the home positions is no greater than 0.10 mm.
The stage should remain stationary before an optical measurement is collected.	Use an oscilloscope or STM32 debug signal to compare the motor-control signal and optical measurement trigger. Verify that the measurement trigger occurs only after motor movement has stopped and a minimum 200 ms settling period has elapsed.
The motion subsystem scans only valid measurement locations within the wafer.	Run the programmed scan pattern without collecting optical data and record the commanded X-Y coordinates. Verify that every measurement coordinate satisfies the effective-radius circle equation.
The wafer should remain fixed in the holder during scanning.	Place the wafer in the holder, mark a reference point on the wafer and holder, and run the complete scan motion. Verify that the relative position of the two reference marks does not visibly change.
The motion subsystem's accuracy of the recorded position and real-life position shouldn't deviate more than 0.25mm.	Command the wafer to take move to a specific x and y coordinate. Check the recorded location of the wafer and then open the enclosure. Using a caliper/ruler measure the exact location of the wafer/stage. Compare the digital and real-life measurements and ensure that there isn't more than a 0.25mm difference.

2.3.3 Data Acquisition and Control

The data acquisition and control subsystem coordinates the wafer scan, collects the optical measurements, and communicates the measurements to the host computer. The subsystem is centered around the STM32G474RET3, which provides the ADC for the optical signal, digital outputs for the stepper motor drivers, GPIO inputs for the limit switches, and communication with the host computer.

The filtered output of the optical sensing subsystem is connected to the STM32's ADC. With 12-bit resolution and a supply of 3.3V, each step will be $\frac{3.3}{2^{12}} = 0.806$ mV step sizes.

At each scan location, the controller will collect 10 samples spaced 10ms apart and average them to obtain the optical measurement. This averaging reduces measurement variation before the result is stored. Each measurement is stored together with the corresponding X-Y position so that the data processing subsystem can generate the wafer map.

The STM32 controls the two DRV8825 motor drivers (one for each axis) using digital step and direction signals. Mechanical limit switches are connected to digital inputs and are used to establish the stage's home

position before scanning. When a scan is completed, the stepper motors will move the stage to the top left corner until it contacts the limit switches and a signal is sent to the microcontroller to stop the motors. The controller must detect a limit switch activation within 10 ms and stop the corresponding motor command. The controller also waits after stage movement before collecting optical measurements so that mechanical vibration does not significantly affect the measurement.

After a scan, the STM32 transmits the collected measurement records to the host computer through a USB connection.

This subsystem directly supports the high-level Wafer Positioning and Spatial Mapping requirement by associating every optical measurement with an X-Y location and supports the Optical Measurement Repeatability and Anomaly Detection requirement by averaging multiple ADC samples at each location.

Requirements	Verification
The data acquisition system should resolve changes in the optical signal of at least 5mV at the ADC input over the expected 0.1–2.7 V signal range.	Apply known voltage levels to the ADC input using a power supply and verify that a 5 mV change produces a distinguishable change in the recorded ADC measurement. Test at multiple points across the input range, such as 1V and 1.005V and 2V and 2.005V
At least 10 ADC samples should be collected at each measurement location with approximately 10ms between samples.	Adjust the code such that timestamps are recorded alongside the ADC samples during a scan and verify that at least 10 samples are collected per location with approximately 10 ms spacing.
The system should average the ADC samples collected at each measurement location before transmitting the measurement.	Adjust the code such that the individual ADC samples are transmitted to the host computer alongside the average. Manually calculate the average of the samples. Verify that the transmitted average corresponds to the calculated average.
Each measurement should include its corresponding X-Y position.	Inspect the transmitted dataset and verify that every optical measurement contains an X coordinate and Y coordinate.
A triggered limit switch shall be detected and cause the corresponding motor to stop within 10ms.	Trigger each limit switch while the motor is moving. Use an oscilloscope to measure the time between switch activation and the motor-stop command. Verify that the difference is no greater than 10ms.

2.3.4 Data Processing and Wafer Mapping

The data processing subsystem will use a host computer running Python to process the optical measurements collected by the STM32G474RET3. Each measurement will be associated with its corresponding X-Y position and compared against the expected baseline optical response. Measurements that differ significantly from the baseline will be identified as potential anomalies.

The software will then display the measurements as a two-dimensional wafer map, allowing the user to see the locations of potential defects and perform targeted microscope inspection. The software will also ensure that all measurements from a complete scan are correctly associated with their X-Y coordinates and produce the same map when processing the same dataset multiple times.

Requirements	Verification
The software should identify measurements that differ significantly from the expected baseline.	Process a dataset containing both baseline measurements and intentionally introduced anomalies. Verify that the anomaly locations are identified after data processing.
The software should display all measurement locations on a two-dimensional wafer map.	Process a complete scan and compare the number of displayed measurement locations with the number of records in the input dataset. Verify that the number of displayed measurements matches the number of input measurements.
The wafer map should correctly represent the spatial locations of identified anomalies.	Use a ruler to place known anomalies at measured wafer locations. Run a full scan. Verify that the displayed map identifies the correct coordinates.
Processing the same dataset multiple times should produce the same wafer map.	Run the same dataset through the processing software at least three times and compare the resulting maps and identified anomaly locations. Verify that they are the exact same.

2.3.5 Enclosure

The enclosure will house the 4-inch wafer, X-Y stage, laser, photodiode, and optical mounts while maintaining their relative positions during operation. It will also reduce the amount of ambient light reaching the photodiode to limit interference with the optical measurements. The laser and photodiode will be mounted to the enclosure so that their positions remain fixed while the wafer moves during scanning.

The enclosure should prevent direct line-of-sight exposure of the photodiode to room lighting and keep ambient-light-induced changes in photodiode current below 5%. Mechanical movement or optical misalignment during a scan should also cause no more than a 5% measurement variation.

The enclosure will be 3D printed in ECEB 2070 using black printing material. The inside of the enclosure may be painted matte black if initial testing reveals unwanted laser refraction.

Requirements	Verification
The enclosure should accommodate the 4-inch wafer, X-Y stage, laser, photodiode, and associated optical mounts without interfering with wafer motion.	Assemble the complete system inside the enclosure and operate the full X-Y scan. Verify that no component interferes with the stage or wafer.
The laser and photodiode mounting positions should remain fixed during operation.	Mark the initial positions of the optical components. Mark where the laser spot hits the stage. Run a scan with no wafer. Inspect the component positions and spot location after repeated scans. Verify no visible shifts.
Measurements taken inside the enclosure should vary no more than $\pm 10\%$ due to outside lighting.	Find a dark room and run a full scan inside the enclosure. Turn on the room lights and run another scan inside the enclosure. Verify that the measurements do not differ by more than $\pm 10\%$.
Mechanical movement of the enclosure or optical mounts should not cause more than a 10% change in the measured optical signal.	Collect measurements from multiple scans under identical conditions. Choose a coordinate to compare across scans. Verify that there is not more than a 10% change in value, especially between the first and last scan.

2.3.6 Power

The power subsystem will use a 24V DC laptop charger as the main power source and to power the DRV8825 motor drivers. A TI LM2596T-5.0/NOPB buck converter will convert the 24V input to 5V for the laser and the reverse bias for the photodiode. A TI TLV70233PDBVR LDO will regulate the 5V rail to 3.3V for the STM32G474RET3, optical sensing circuitry, and other 3.3V components. Decoupling capacitors and power filtering will be included to reduce voltage fluctuations and electrical noise from the stepper motor drivers.

The 24 V supply was selected because it is within the DRV8825 operating voltage range and allows the drivers to regulate the 1.5 to 1.7 A/phase NEMA 17 motors. Decoupling capacitors will be placed near the motor drivers, STM32, and analog circuitry to reduce voltage fluctuations caused by motor switching. The motor and analog power paths will be separated where practical to reduce electrical noise in the photodiode measurement.

Requirement	Verification
Provide a 24V supply through a laptop charger to both DRV8825 drivers with a swing of no more than $\pm 5\%$.	Measure the voltage at each driver while the motors are running. Ensure that the measured voltage is within 22.8-25.2V.
Maintain the 3.3 V rail within $\pm 5\%$.	Measure the 3.3 V rail with motors stationary and operating. Ensure that voltage remains between 3.135 V and 3.465 V.
Supply the laser and optical circuitry with 5 V $\pm 5\%$.	Measure the 5 V rail during normal operation. Ensure that voltage remains between 4.75 - 5.25V.
Limit motor-induced measurement error to $\leq 5\%$.	Take photodiode measurements while the motors

	are stationary and moving. Compare the measurements under both scenarios and ensure that the optical signal change is $\leq 5\%$.
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2.4 Tolerance Analysis

The optical sensing subsystem was selected as the most critical block because its measurement consistency directly determines whether the system can reliably identify abnormal wafer regions. The subsystem must account for variation introduced by the laser, photodiode, wafer reflectivity, amplifier, filter, and ADC. Therefore, the following tolerance analysis examines the major sources of error in the optical signal chain and determines whether their combined effects can be kept within the required measurement tolerance.

We start by citing the requirement of the optical sensing system in **1.4** again:

For each datapoint, the sensing system will do consecutive measurements under identical conditions. We defined the datapoint to be “consistent” if all the measurements made at the position of the datapoint are within $\pm 10\%$ of the set’s average value.

Anomaly detection is carried out by comparing the datapoint’s measured optical response with a baseline distribution of “acceptable” wafer measurements. Based on the baseline distribution, Gaussian distribution parameters μ and σ are derived. Thus, an anomaly is recognized when its’ optical response is outside the range of $\mu \pm k\sigma$. We will for now keep the value of k undeclared for further analysis.

The optical sensing system flow is as follow: The laser beam reflects on the wafer’s surface to reach the photodiode opening – which induces a photodiode current I_{PD} . As discussed in section 2.3.1, the current goes through OPA380 with a feedback resistor R_F to amplify the output voltage V_{TIA} :

$$V_{TIA} = I_{PD}R_F$$

An RC filter then is utilized to filter out unwanted noise from the voltage output signal V_{TIA} before it is connected to the ADC in STM32 microcontroller. We list off the errors of the components:

Components	Errors name	Values, errors and notes
Laser	Output power tolerance:	$P_0 = 5 \text{ mW} \pm 0.5 \text{ mW}$
	Wavelength uncertainty	$650 \pm 10 \text{ nm}$
BPW34 photodiode	Responsivity uncertainty at laser’s wavelength	Refer to below for calculation
Wafer	Reflectivity of the wafer	Refer to below for the explanation
Feedback resistor	Resistance uncertainty	Comes from designing value, typically taken from the datasheet
RC low pass filter	Source impedance into the ADC	$R = 1 \text{ k}\Omega$ is under the RAIN max at 47.5 cycles (fast: $2.2 \text{ k}\Omega$, slow: $1.8 \text{ k}\Omega$), per Table 67 of [4]
ADC in STM32	Offset error	$\pm 4 \text{ LSB max (T68)} / 5.5 \text{ (T70)} \approx 3 \text{ to } 4.4 \text{ mV}$, calibratable

From the basic characteristic table, we can see that the reverse current at $\lambda = 950 \text{ nm}$; $E_e = 1 \text{ mW/cm}^2$ and reverse bias of 5 V is minimum of $40 \text{ }\mu\text{A}$ and typically $50 \text{ }\mu\text{A}$. Power incident on the diode is $P = E_e \times S = 75 \text{ }\mu\text{W}$. Responsivity is thus:

$$S(\lambda = 950 \text{ nm}) = \frac{I_{ra}}{\text{Incident power}} \left[\frac{\text{A}}{\text{W}} \right]$$

Thus, with the lower and typical value of reverse current, we obtain:

$$S(\lambda = 950 \text{ nm}) = [0.53; 0.67] \left[\frac{\text{A}}{\text{W}} \right]$$

At 650 nm , the relative sensitivity is $S(\lambda = 650 \text{ nm}) = 0.6$ while that at 950 nm is approximately 0.98 (Fig. 7 - *Relative Spectral Sensitivity vs. Wavelength – BPW34 datasheet*). Given that, the sensitivity at 650 nm is:

$$S(\lambda = 650 \text{ nm}) = S(\lambda = 950 \text{ nm}) \times \frac{S_{rel}(650)}{S_{rel}(950)} = [0.3245; 0.4102] \left[\frac{\text{A}}{\text{W}} \right]$$

With incident power P_{laser} (from the laser and minus any lost from the wafer and pathway), we can find the current in the photodiode to be:

$$I_{PD} = S(\lambda = 650 \text{ nm}) \times P_{laser} [\text{A}]$$

The total current could also comprise of the dark current at higher temperature. However, we expect the operating to be at room temperature – therefore the total current consists of photodiode current I_{PD} mostly.

Incident reflectivity of Silicon is given by:

$$R = \left(\frac{n - 1}{n + 1} \right)^2$$

...where n is the refractive index. At incident wavelength of 650 nm , the refractive index $n = 3.815$ which give $R = 0.3418$ [6]

Laser wavelength uncertainty is $\pm 10 \text{ nm}$, which gives the range from $640 - 660 \text{ nm}$. Range of refractive index is then $n = [3.8365; 3.8696]$ and result in $R = [0.3439; 0.3473]$

With $P_{laser} \approx P_0 \times R$ for no defect point, we expect $I_{PD} = S(\lambda = 650 \text{ nm}) \times P_0 \times R$

Therefore:

$$V_{TIA} = I_{PD} R_F = S(\lambda = 650 \text{ nm}) P_0 R R_F [\text{V}]$$

V_{TIA} is fed into the RC filter and then into ADC converter of the microcontroller. The data is then converted into ADC's output code:

$$N = \frac{V_{ADC}}{V_{REF}} \times 2^{12}; V_{REF} = V_{DD} = 3.3 \text{ V}$$

The ADC's output code is:

$$N = \frac{S(\lambda = 650 \text{ nm})P_0RR_F}{V_{REF}} \times 2^{12}$$

Now, our job is to find the error propagation:

$$\Delta N = \sqrt{\left(\frac{\Delta S}{S}\right)^2 + \left(\frac{\Delta P_0}{P_0}\right)^2 + \left(\frac{\Delta R}{R}\right)^2 + \left(\frac{\Delta R_F}{R_F}\right)^2}$$

With all the calculations above:

$$\begin{aligned} S &= 0.36735 \pm 0.04285 & \left[\frac{A}{W}\right] \\ P_0 &= 5 \pm 0.5 & [mW] \\ R &= 0.3456 \pm 0.0017 \\ R_F &= R_F \pm \Delta R_F & [\Omega] \end{aligned}$$

We can find the uncertainty ΔN . Such uncertainty for a perfect wafer should not exceed $k\sigma$ for anomaly detection criteria stated above, while for “consistent” criteria, it should be less than 10% of the averaged values.

$$\Delta N \leq k\sigma_N \text{ and } \Delta N \leq 0.1\mu_N$$

The criteria above must be always maintained to prevent “false positive” measurement. Therefore, our choices of equipment must be closely examined to maintain the validity of above statement. Value k is chosen when we examine samples of test wafer in benchmark with no-defect wafer. σ_N and μ_N should then be derived from the samples’ data set!

That being said, the model above is still very simple and missing out many uncertainties. For example, mechanical uncertainty in the wafer motion and positioning system is not considered yet. Further discussion with team member and Teaching Assistant will be carried out in the future to arrive at a perfect model. This is significance since our system requires extremely small uncertainty to ensure the small-scale nature of the problem statement to be fully solved.

3. Cost and Schedule

3.1 Cost Analysis

3.1.1 Labor

Assuming an average starting salary of \$87,429 per year for a UIUC ECE graduate and a standard 2,080-hour work year, the equivalent hourly rate is approximately \$42.03/hour. Assuming each team member contributes an average of 10 hours per week over the 16-week semester, with a 2.5× labor multiplier, the estimated labor cost per team member is:

$$\$42.03 \times 10 \times 16 \times 2.5 = \$16,812.00$$

For a three-person team, the total estimated labor cost is:

$$\$16,812.00 \times 3 = \$50,436.00$$

Therefore, the estimated total labor cost for the project is approximately **\$50,436**.

3.1.2 Parts

Part Name	Website	Part #	Qty	Unit Cost (\$)	Total Cost (\$)
NEMA 17 bipolar stepper motor	StepperOnline	17HS15-1704S	2	4.70	9.40
Stepper motor driver	Texas Instruments	DRV8825	2	15.95	31.90
Linear rail + carriage	Limo Bearing	MGN7H MGN7C Miniature linear ball rail 150mm	2	7.71	15.42
Laser	Adafruit	Laser Diode - 5mW 650nm Red	1	5.95	5.95
Tr8x8 Lead Screw with T8 Brass Nut	Amazon	2PCS 300mm (11.81 Inches) Tr8x8 Lead Screw with T8 Brass Nut (Acme Thread, 2mm Pitch, 4 Starts, 8mm Lead) for LCD DLP SLA 3D Printer Z Axis and CNC Machine	1	11.99	11.99
3.3-V LDO regulator	ECE 445 Lab	TLV73333PDBVR	1	Free	Free
STM Microcontroller	STMicroelectronics/DigiKey	STM32G474RET3	1	10.92	10.92
Transimpedance Amplifier	Texas Instruments	OPA380AID	1	5.27	5.27
Photodiode	Vishay/DigiKey	BPW34	1	1.37	1.37

Limit Switches	DigiKey	D2F-01L2	2	3.03	6.06
Coupler	DigiKey	COUPLER-5MM8MM-FLEX	2	1.45	2.9
Buck Converter 24V -> 5V	DigiKey	LM2596T-5.0/NOPB	1	5.67	5.67
24V 5A DC Power Adapter	SHINTPWR	4V DC Power Supply 24 Volt 5A 120W Power Adapter 100V~240V AC to DC Converter Transformer 5.5x2.5mm Plug for 5050 3528 LED Strip Light 3D Printer LED Driver CCTV Security System LCD Monitor	1	20.99	20.99
CONN PWR JACK	DigiKey	694108301002	1	0.97	0.97

Machine shop hours: A full design would use machined parts instead of 3D printing. We estimate approximately 8 hours of machine shop labor to fabricate the custom mechanical components, including the X-Y stage plates, motor/rail mounting features, lead screw mounting features, and wafer holder/enclosure components. This estimate assumes that the major motion components, including the linear rails, lead screws, motors, and couplers, are purchased and only the custom structural components require machining.

Machine Shop Rate = \$60/hr.

Machine Shop Cost = 8 * 60 = \$480.

3.1.3 Sum of Total Cost

Parts Total

$0.97 + 20.99 + 5.67 + 2.90 + 6.06 + 1.37 + 5.27 + 10.92 + 11.99 + 5.95 + 15.42 + 31.90 + 9.40$
= \$128.81.

Labor Total

= \$50,436

Machine Shop Total

= \$480.

Grand Total

= \$128.81 + \$50,436 + \$480 = **\$51,044.81.**

3.2 Schedule

Week #	Tasks	People
10/5	• Design Review with TAs • Complete PCB audit and required revisions • Submit second-round PCB order • Finalize optical sensing circuit • Continue mechanical design and enclosure development	• All • All • All • Josh and Minh • Megan
10/12	• Breadboard optical sensing circuit and test photodiode/TIA response • Submit third-round PCB order after required audit • Order remaining electronic and mechanical components • Begin STM32 firmware for ADC acquisition and motor control	• Josh • All • Megan • Minh
10/19	• Test and characterize optical sensing subsystem • Assemble and test X-Y stage and stepper motors • Develop initial raster scanning routine • Prepare PCB design for fourth-round submission	• Josh • Megan • Minh • All
10/26	• Submit fourth-round JLCPCB order • Complete PCB audit and final hardware revisions • Continue firmware development for ADC sampling, motor control, and communication • Begin wafer mapping software	• All • All • Minh • Megan
11/2	• Progress Demo with TAs • Assemble available hardware and begin subsystem integration • Test communication between STM32 and host computer • Begin integrating optical measurements with X-Y position data	• All • Megan • Minh • Josh
11/9	• Integrate PCB, optical sensing, and X-Y stage • Calibrate stage positioning and homing • Characterize optical measurement repeatability • Test detection of photoresist residue, scratches, and other surface anomalies • Establish scan spacing and measurement parameters	• All • Megan • Minh • Josh • Megan
11/16	• Mock Demo with TA • Mock Presentation with TA • Perform full-system scanning tests • Verify wafer mapping and anomaly detection • Resolve remaining hardware and software issues	• All
11/23 (Fall Break)	• Fall Break • Complete any remaining testing or documentation as needed	• All
11/30	• Final Demo and Presentation • Complete final system verification • Finalize wafer mapping software and results	• All • Minh • Megan

	• Complete final design documentation	• Josh
12/7	• Final paper due • Lab notebook due • Finalize remaining project documentation	• All

4. Ethics, Safety and Societal Impact

4.1 Societal Impact

The project is intended to demonstrate a lower-cost approach to automated wafer inspection that could make basic semiconductor manufacturing inspection more accessible for educational and research applications, especially in classes such as ECE 444. Automated inspection can reduce the amount of manual inspection required and can provide consistent measurements across a wafer. However, an inaccurate inspection system could cause usable material to be incorrectly classified as defective or allow actual defects to be missed. For this reason, the prototype should be considered an inspection aid rather than a replacement for qualified semiconductor inspection equipment.

The system may also reduce material waste by identifying areas of a wafer that show abnormal optical behavior before additional processing steps are performed. More broadly, developing accessible semiconductor inspection technology can support education and research by allowing students and smaller laboratories to experiment with wafer-level measurement techniques without requiring access to expensive commercial inspection systems.

4.2 Engineering Standards

Several engineering standards and professional guidelines are relevant to the project.

Laser safety: The 650-nm, 5-mW laser falls at the upper limit of the Class 3R category according to the University of Illinois laser classification guidance. Class 3R lasers can be hazardous under direct or specular-reflection viewing conditions. The relevant international standard is IEC 60825-1, Safety of Laser Products – Part 1: Equipment Classification and Requirements, which addresses laser-product classification and safety requirements. UIUC also uses laser-safety procedures based on ANSI Z136.1.

Electrical safety: The project uses a 24-V DC power supply connected to a wall outlet. The AC side of the power supply must remain enclosed and must use an appropriately rated commercial power supply. NFPA 70 (National Electrical Code) provides requirements intended to reduce electrical shock, fire, and equipment hazards.

Power-supply safety: UL/IEC 62368-1 is a relevant product-safety standard for equipment and power supplies in applicable information and electronic equipment categories.

4.3 Ethics

The project follows the principles of the IEEE Code of Ethics by placing safety and public welfare above project performance and by requiring the team to make honest claims about the accuracy and limitations of the prototype. The IEEE Code also emphasizes honestly reporting technical results and acknowledging and correcting errors.

The ACM Code of Ethics is also relevant because the STM32 firmware controls the automated measurement process and determines how measurement data are collected and interpreted. The ACM Code emphasizes contributing to human well-being, avoiding harm, and considering the broader effects of computing systems.

A major ethical concern is the possibility of reporting inaccurate wafer-defect measurements as if they were definitive. The team will therefore report the system's measured accuracy and limitations rather than claiming performance that has not been experimentally verified. Another concern is data integrity: measurement data should not be selectively removed or altered simply to improve the apparent performance of the prototype. All relevant testing results, including unsuccessful tests and measurement errors, should be documented honestly.

4.4 Electrical Safety

The system receives power from a 24 V DC supply connected to a wall outlet. Although the system's internal motor supply is 24 V DC, the wall outlet and the AC input to the power supply present a higher electrical hazard. Users should not touch exposed conductors, the AC input terminals, or damaged power cables while the system is energized.

The AC power supply will therefore remain enclosed, and all exposed low-voltage wiring will be insulated. Connections will be strain-relieved where appropriate, and wires will be secured so that moving components cannot pull on electrical connections. The 24-V supply will feed the DRV8825 motor drivers, while a DC-DC converter will generate the lower-voltage 5-V rail for the laser and analog circuitry. The STM32 will receive 3.3 V through the appropriate regulator.

The system will be disconnected from the wall before modifying wiring, replacing components, or performing mechanical maintenance. The power supply will also be mounted securely so that it cannot contact conductive parts of the mechanical stage.

4.5 Mechanical Safety

The X-Y stage contains moving lead screws, rails, motor couplers, and a moving wafer platform. These components can create pinch points or unexpected motion during operation. The housing will therefore separate the moving mechanism from the user as much as practical, and users will not place their hands near the stage while the motors are energized.

The mechanical limit switches will establish a repeatable home position and prevent the firmware from relying solely on accumulated step counts after startup. The stage will also be tested at low speed before full-speed operation to verify that the rails, lead screws, couplers, and motor mounts are properly aligned.

Fabrication will follow University of Illinois shop-safety requirements. Appropriate PPE, including safety glasses, will be used during machining, and only trained users will operate machine-shop equipment. UIUC shop-safety guidance emphasizes that improperly used machine-shop equipment can result in serious injury and that appropriate safety procedures must be followed.

4.6 Laser Safety

The 650-nm laser presents an optical hazard because its 5-mW output is within the Class 3R range. Direct viewing of the beam and specular reflections from reflective surfaces such as the wafer must therefore be avoided.

The laser will be mechanically mounted so that the beam is directed only toward the intended measurement area. The housing will be designed to enclose the beam path as much as practical and prevent accidental viewing of the direct beam. Reflective surfaces near the beam path will be minimized, and a beam stop will be provided at the end of the optical path where appropriate.

UIUC laser-safety guidance recommends stable laser mounting and controlling or enclosing the beam as much as practical. Because this project is being developed at UIUC, the team will follow applicable Division of Research Safety requirements and complete any required laser-safety training or registration before operating the laser in a university laboratory. UIUC identifies laser registration and authorization as part of its campus laser-safety program.

4.7 Safety Mitigation Procedures

The following procedures will be used to reduce project risks:

1. **Disconnect wall power before servicing:** The AC power connection will be disconnected before modifying or repairing the electrical system.
2. **Enclose the AC supply:** The wall-powered portion of the system will not have exposed conductors accessible during normal operation.
3. **Insulate low-voltage wiring:** All 24-V, 5-V, and 3.3-V conductors will use insulated wiring and secure connections.
4. **Limit motor current:** The DRV8825 current limit will be configured for the selected NEMA 17 motors to prevent excessive motor and driver heating. The DRV8825 provides adjustable current limiting and over-temperature/over-current protection.
5. **Use mechanical homing:** Limit switches will establish the initial X-Y reference position before scanning.
6. **Protect moving components:** The housing will reduce access to moving lead screws, couplers, and pinch points during normal operation.
7. **Enclose the laser beam:** The optical path will be enclosed as much as practical and directed away from users.
8. **Use a beam stop:** The laser beam will be terminated at a controlled location rather than allowed to propagate beyond the measurement region.
9. **Test at low speed first:** Initial mechanical tests will use reduced motor speed to identify alignment problems before normal operation.
10. **Verify measurement performance:** The team will compare repeated measurements and known test conditions before relying on the system's defect-detection results.
11. **Document limitations:** The final report and demonstration will clearly identify measurement errors and limitations rather than presenting the prototype as equivalent to commercial semiconductor inspection equipment.

These measures are intended to protect both the users and developers by addressing the primary electrical, optical, mechanical, and data-integrity hazards identified during the design process.

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