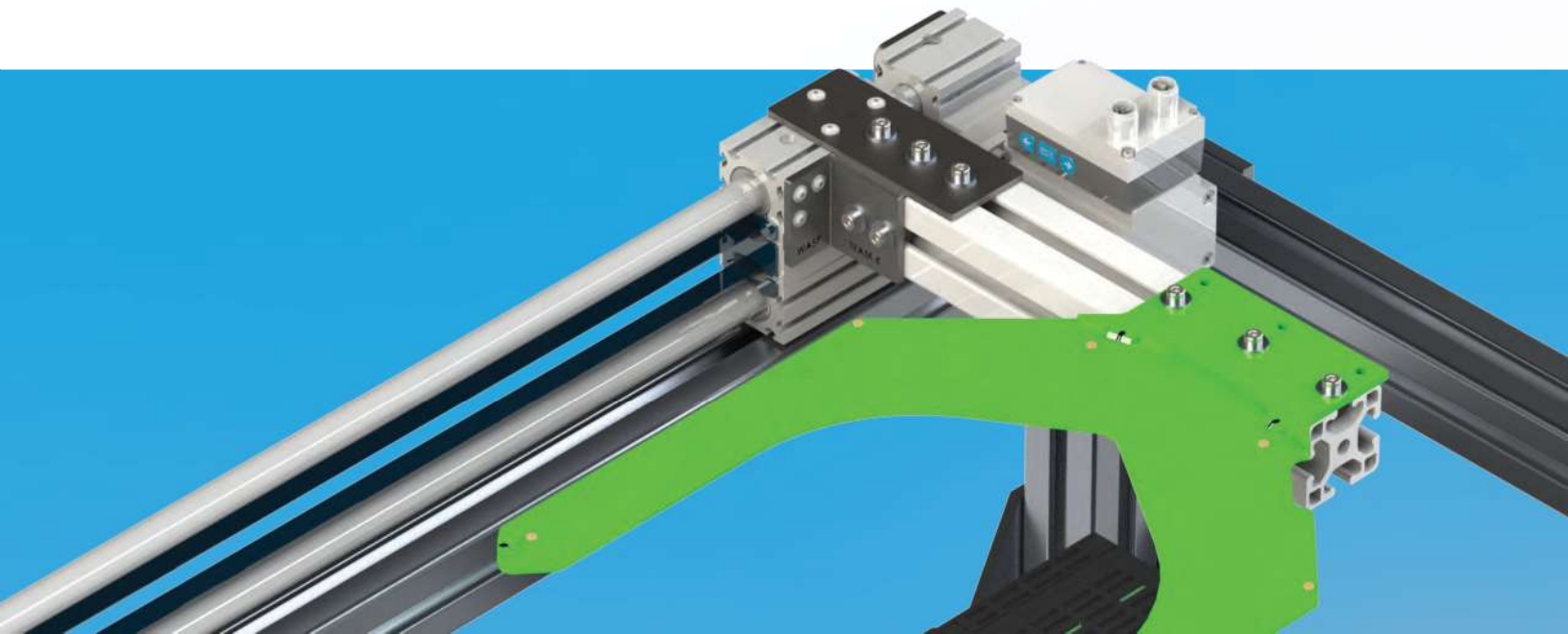


University of Colorado Boulder | Team 4
KLA | Design Center Colorado

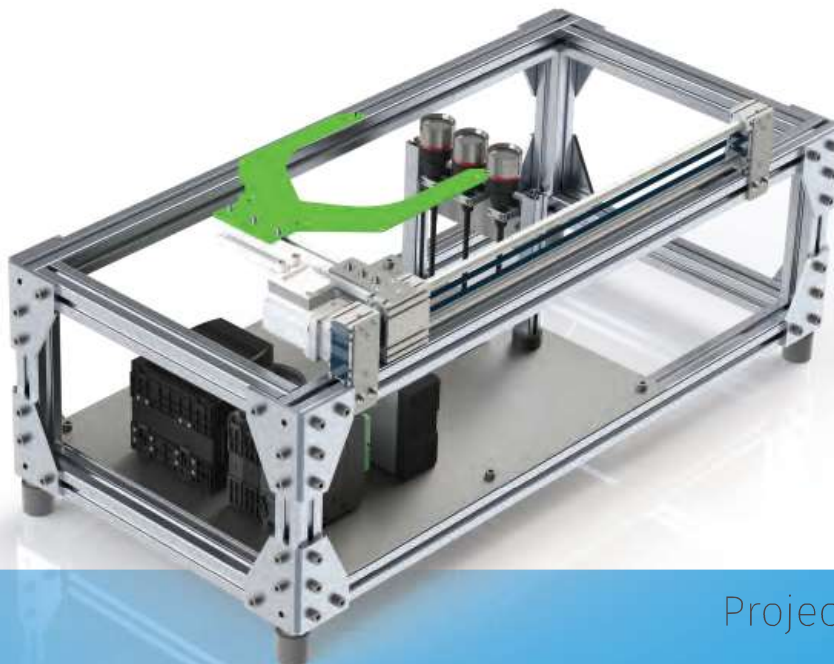
Project WASP

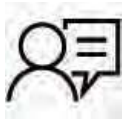
Project WASP (Wafer Automated Surface Profiler) explores non-contact silicon wafer measurement methods for the semiconductor industry.



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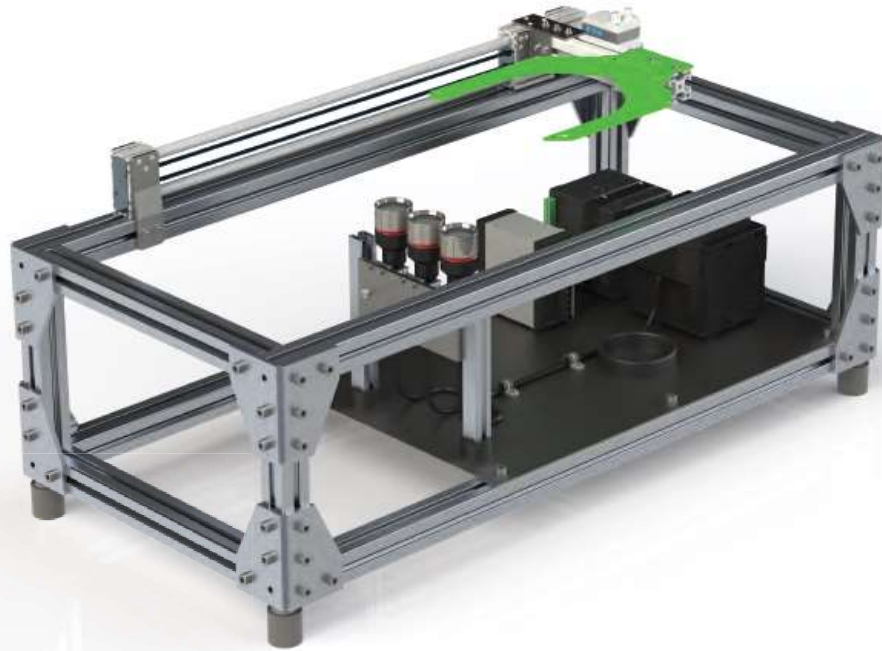
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Introduction

Project WASP, or Wafer Automated Surface Profiler, is an end-to-end proof of concept wafer metrology system. The team's goal is to prevent micro deformities from going undetected in tight tolerance production lines. Extremely tight specifications make it easy to miss an over-warped wafer, resulting in lost revenue every year. This white paper outlines the process taken to meticulously analyze, design, build, and test a benchtop metrology system capable of outputting highly sensitive and repeatable surface profiles of wafers in an automated environment.



Render Image



Final Assembly

This project has the potential to assist a wide array of industries, but it has been designed specifically for semiconductor manufacturing purposes. Over 10 months, the undergraduate team has worked closely with KLA, an industry leader in process control and computational analytics out of San Francisco, CA, to develop and fund an implementable end product.

Although there is room for improvement, the team is confident that their metrology system will prove crucial towards quality control of all products, helping industry processes become increasingly more efficient.



System Requirements

Benchtop Testing System

Project WASP includes the development of a benchtop testing system. While this benchtop system will not be implemented at KLA, it is designed to mimic silicon wafer transfers that happen in house. The goal of this system was to create a repeatable motion process that can be used to validate the function of our sensor array and software. The benchtop testing system holds to the following specifications:

- Similar wafer transfer speeds equivalent to in-house systems
- Volume constraints designed to interoperate with client systems
- Static and dynamic deflection no more than 10 micrometers during wafer transfer

Probe selection

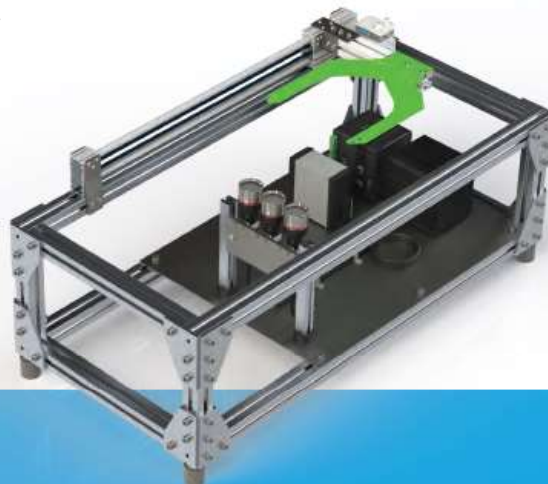
The use of non-contact sensors to detect surface deformities can be seen across various past designs and research documentation. There are multiple possible technologies that can be leveraged for this use including eddy current, capacitance, laser triangulation, confocal chromatic, and fiber optic measurement. Sensor selection is critical for the development of our product. The selected sensor array takes the following engineering requirements into consideration:

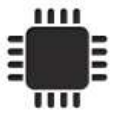
- Non-contact
- ISO5 Cleanroom compliant
- Sensitivity of 10 micrometers
- Repeatability of 100 micrometers
- Compact with a large working range and stand-off distance
- High sampling rate

Software

A major component of this project is the software integration used to process the data received from the sensors post-capture. The goal of this software is to analyze the distance measurements from the sensor array and determine a number of attributes of the wafer. To accomplish these goals, the team implemented several algorithmic tools to refine the raw data and interpolate missing data. The software was held to the following requirements:

- Acquire and process data during wafer motion (one wafer processed every 5 seconds)
- Repeatability of 100 microns





Hardware

Frame

40-series 8020 extruded aluminum was utilized to build the test bench structure due to its adjustability and high strength-to-weight ratio. The 8020 40-series frame has exterior dimensions of 1m (L) x 0.48m (W) x 0.3m (H) (3.28 x 1.57 x 0.98 ft) and each member has a cross-sectional area of 8.742 cm². All fasteners used in the frame are standard 8020 off-the-shelf fasteners sized at M8x16mm machine screws and 'T-nuts'. The total system height comes to 0.35m (1.15 ft) and weighs approximately 24.32 kg (53.61 lbs).



The Frame

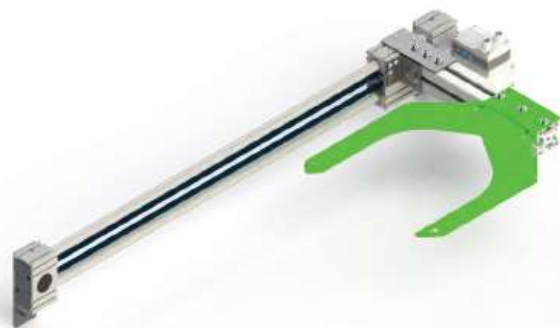
Motion Simulation

Festo's toothed belt axis unit (8083936) linear actuator was chosen to simulate the movement of client's robotic arm as well as meet velocity and acceleration requirements. The linear actuator has a built-in encoder, end-position sensing, overheating protection, and automatic homing to produce the necessary parameters below:

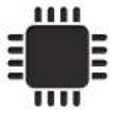
- Maximum payload supported: 2.8 kg at full stroke
- Maximum acceleration allowed: 8.5 m/s²
- Desired maximum acceleration: 3 m/s²
- Maximum speed supported: 1.2 m/s
- Desired speed: 0.7 m/s
- Maximum stroke allowed: 600 mm
- Desired stroke: 464 mm
- Maximum force supported: 50 N at full stroke



Festo Linear Actuator



Motion Simulation System



Hardware

Sensor Systems

The WASP system, as a proof of concept, consists of one displacement lens which has a housing diameter of 46mm. The sensor has a standoff distance of 60mm and a working range of 70 ± 10 mm. This lens has a high resolution with a measurement repeatability of $2.2 \mu\text{m}$. The system also requires the use of one optical unit, one controller, and one power supply unit. A major benefit of this system is that it provides automatic noise and vibration isolation which will allow the system to pre-process the data and remove the noise of mechanical vibrations from the measurements, greatly improving the reliability and accuracy of the system's measurements and analysis.



Displacement Sensor



**Sensor Mounting System
(Full Range of Positions)**

Sensor Mounting

The sensor mounting system is responsible for holding and isolating the sensor for proper measurements when the test wafers are passed over the array from above. The mounting structure is made of 25 series 8020 extruded aluminum and a custom made sensor clamp to 8020 adaptor so that sensor mounting position is adjustable within a range of about 200mm (7.87 in) side-to-side and up to 155mm (6.10 in) vertically. This mounting system was designed to take system vibrations into account with the option for four vibration isolating feet to separate the mounting structure from the rest of the testing system.



Software

Introduction

The WASP algorithm takes real world data and extracts vital topographical information from it.

Input

A set of 'watchdog' programs constantly monitor the input folders designated by the user for new csv files. When a new file is detected, it is renamed and moved to the appropriate folder specified in the data processing block.

Data Processing

The algorithm diverges and takes one of two paths; one for a multiple sensor setup and another for a single sensor setup.

Single Trace Analysis

In the single trace block, the csv file is parsed into an array and a complementary x-value array is generated. These two arrays comprise the x and y data that is used to fit a 2nd-order curve to the data whose equation is then optimized within the bounds of the original dataset.

Similarly in the multiple traces block, the algorithm first waits to receive all the traces from a single run. It then generates a point cloud by assigning appropriate x and y values to the raw data which makes up the z values.

Multi-trace Analysis

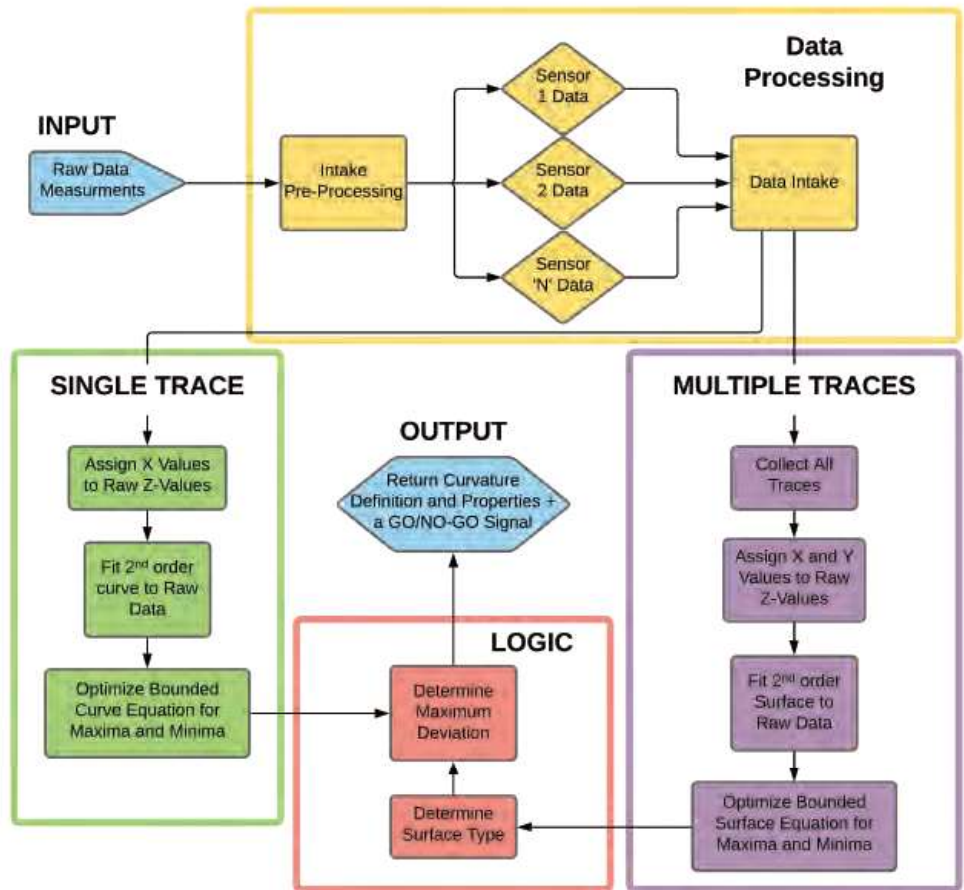
Similarly in the multiple traces block, the algorithm first waits to receive all the traces from a single run. It then generates a point cloud by assigning appropriate x and y values to the raw data which makes up the z values.

Logic

This point cloud is used to fit a 2nd-order surface that represents the collective sum of the point cloud and its equation is optimized to obtain the maximum and minimum points on the surface. Both paths reconverge in the logic block where, in the multiple trace case, a surface type is identified, either concave, convex, or saddle.

Output

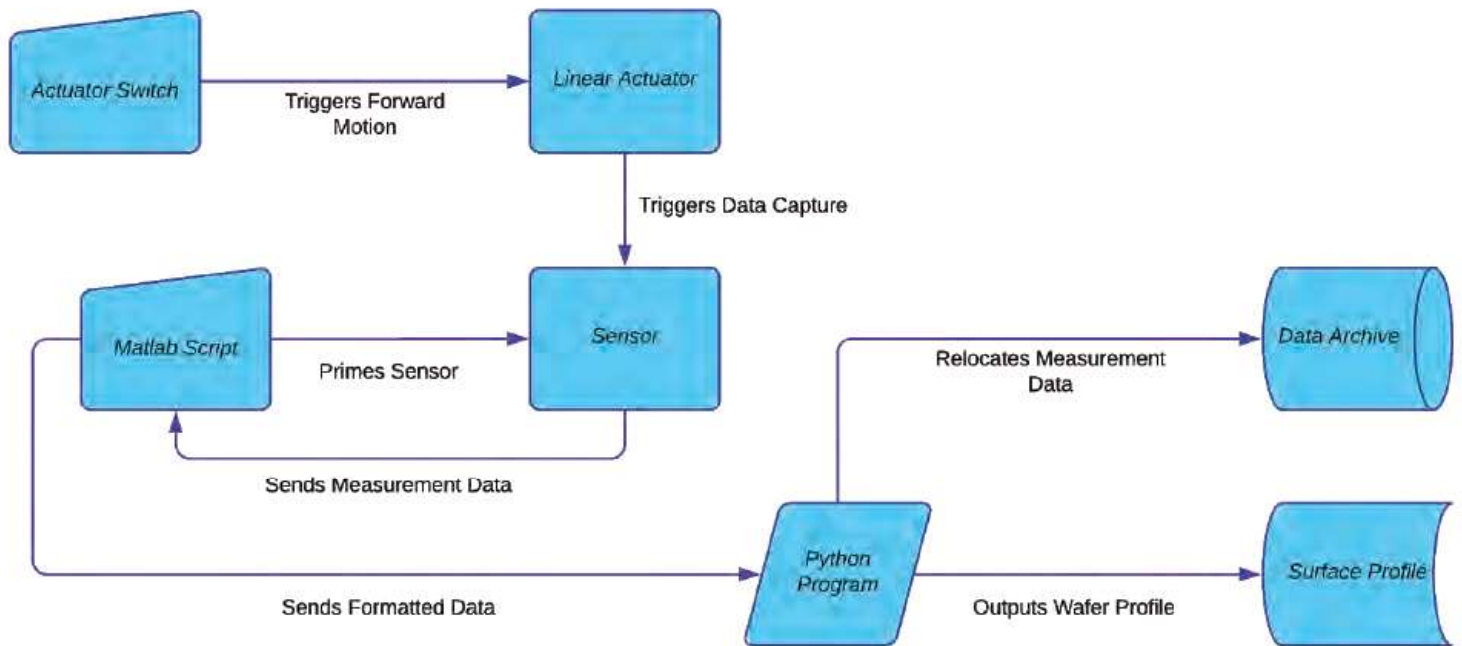
Both 3D and 2D options also use the maximum and minimum points to determine the maximum height variance in the surface and the algorithm outputs these properties along with a GO/NO-GO signal as a final result. Previous run csv files are stored in a rolling archive that is managed by another 'watchdog' program.



Software Diagram



System Operation



Mechanical Motion

Project WASP utilizes three primary systems that operate in tandem to capture and process data. The first two systems are the electronic hardware components of the system, specifically the linear actuator and the sensor, and the last would be the computer itself, which acts as the data capture and processing center. The linear actuator is the only piece of the system that is run without the use of the computer; it operates through settings via the built-in human-machine interface (HMI) and an electronic switch. The switch utilizes three settings: forward motion, no motion, and reverse motion. This switch utilizes digital IO communication to trigger this movement. For fully automated movement, a programmable logic controller (PLC) is required, along with an additional controller for the linear actuator. These components were deemed unnecessary in the scope of this project, and would have tripled the project budget.

Data Acquisition and Processing

The sensor runs continually, and requires no specific input for the system to run. The computer captures the data measured by the sensor, and the communication between the two systems is performed via Ethernet IP. The data capture settings are configured within the included software for the sensor, while the triggering and data formatting is handled by a Matlab script. Once the data is formatted, it's saved in a target folder that is watched by a Python program. The Python program processes the data to create a profile of the wafer and then moves the original data into a different folder to archive the raw data if needed.



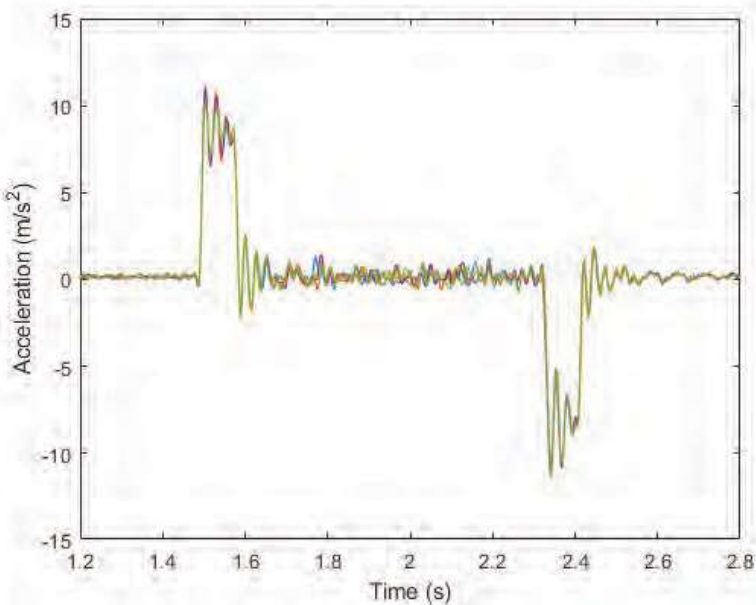
Testing

Testing Introduction

Testing is an imperative component of this project. As the majority of requirements rely on the repeatable operation of the system, all preliminary analysis was verified through testing. Linear motion was verified to ensure reliable movement of the wafer. Vibration testing was performed on the frame, the sensor mounting system, and the wafer motion system to ensure that no additional noise is introduced via the linear actuator or otherwise. Lastly, measurements were taken to determine the repeatability of the system; in this stage the velocity of the motion was tested and minor adjustments were made to meet the repeatability criteria set by the requirements.

Motion Simulation Validation

In order to accurately process the incoming data from the sensor, the velocity of the linear actuator was determined using an accelerometer. This velocity was found to be 0.733 m/s with a standard deviation of 0.0032 m/s (30 trials). That level of repeatability meets our requirements and allows for an accurate determination of the position values with their corresponding heights.



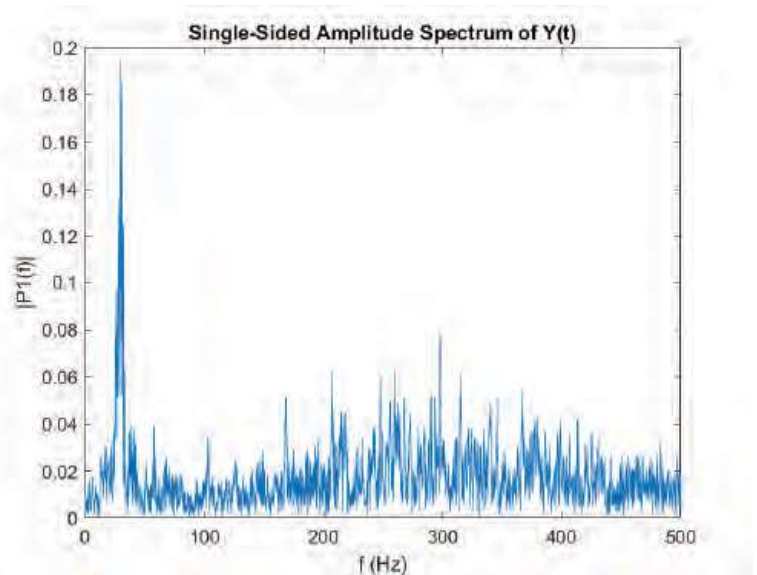
Wafer Velocity Acceleration Plot

Vibration Testing

The objective of these tests was to determine the vibrations occurring throughout the system at critical locations including on the side of the linear actuator, on the wafer handling cantilever, and on the sensor mounting system. These locations were selected for the purpose of identifying where vibration is occurring and determining whether it is within a threshold that is accept-

able or if further vibration dampening must take place. The tests were performed using a three axis accelerometer and indicated that the sensor mounting system, the frame, and the linear actuator were not experiencing considerable vibration. However, the wafer handling cantilever showed higher vibrations in the z-axis, which could have negative effects on data collection. This vibration was further analyzed through measurements via the displacement sensor.

The analysis of the wafer handling cantilever, for which the Fourier analysis is shown below, showed the presence of 30 Hz vibrations. These low frequency vibrations were determined to be caused by the guidance rods on the linear actuator.



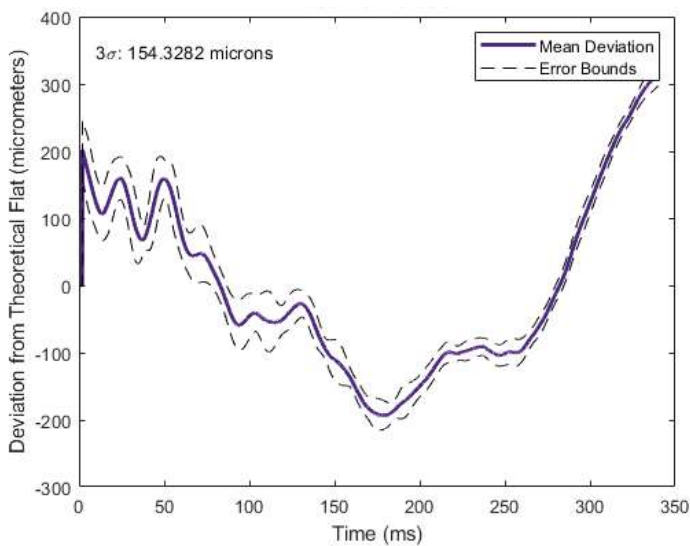
Fourier Analysis of the Wafer Handling Cantilever



Testing

Baseline System Testing

As forecasted by the vibration testing, the system testing indicated the presence of vibrations in the z-axis. The vibrations, which are better described as oscillations, source from the movement of the wafer attached by a cantilever arm. These oscillations are caused by deflection of the guidance rods in the Festo actuator. Baseline testing was performed on a known-flat wafer to determine the initial repeatability of the system.



Baseline Data and its Repeatability

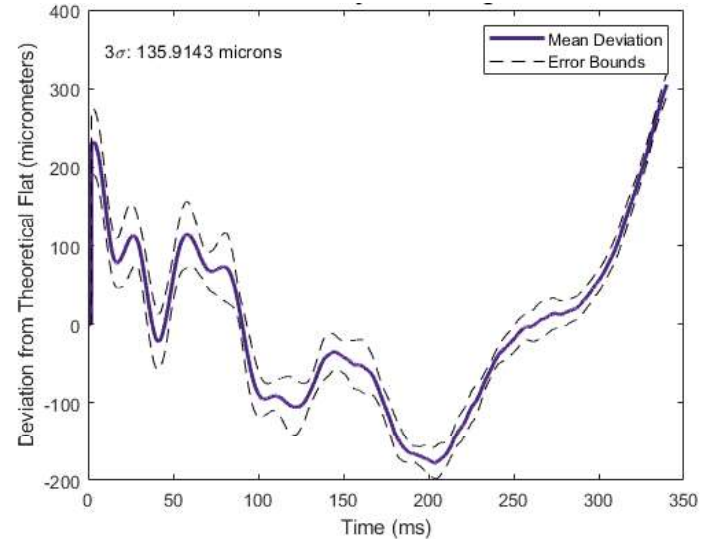
The repeatability of this system was determined to be 154 microns (3-sigma). The purpose of determining this repeatability is to add a correction curve in the data processing to correct for this oscillation. The achieved repeatability is outside of the requirement range, so further adjustments were made to bring this value down to 100 microns.

Tuning the System

In order to tune the system and maximize repeatability, all possible adjustments were identified and tested.

Two main aspects were analyzed to improve the performance of the system: increasing the travel speed of the wafer and the addition of a counter-weight to offset the cantilever of the wafer mounting system.

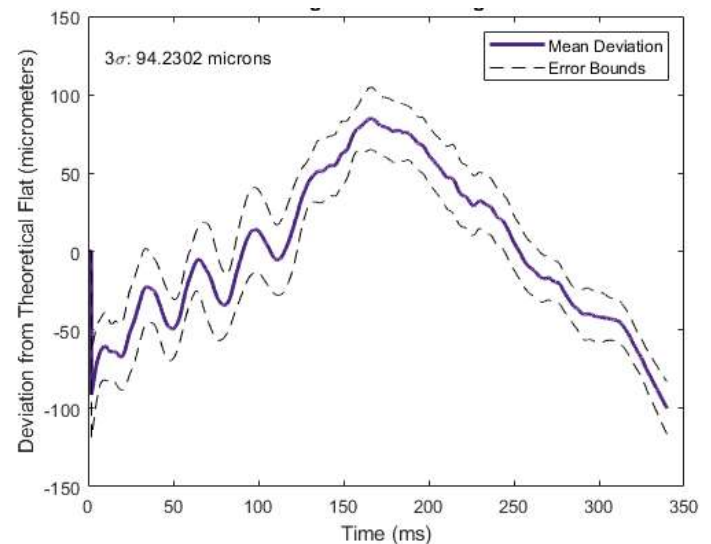
The addition of the counter-weight and increasing the wafer travel velocity to 1.2 m/s improved the repeatability by 15 and 10 microns respectively.



Counter-weight Data and its Repeatability

Final System Performance

Combining these adjustments with a more permanent counter-weight yielded a repeatability of 94.2 microns, closely matching the requirements. This improved repeatability allows our system to take on a reliable calibration curve in data processing and surface analysis to accurately measure the system, process the data, and perform logic to determine wafer condition.



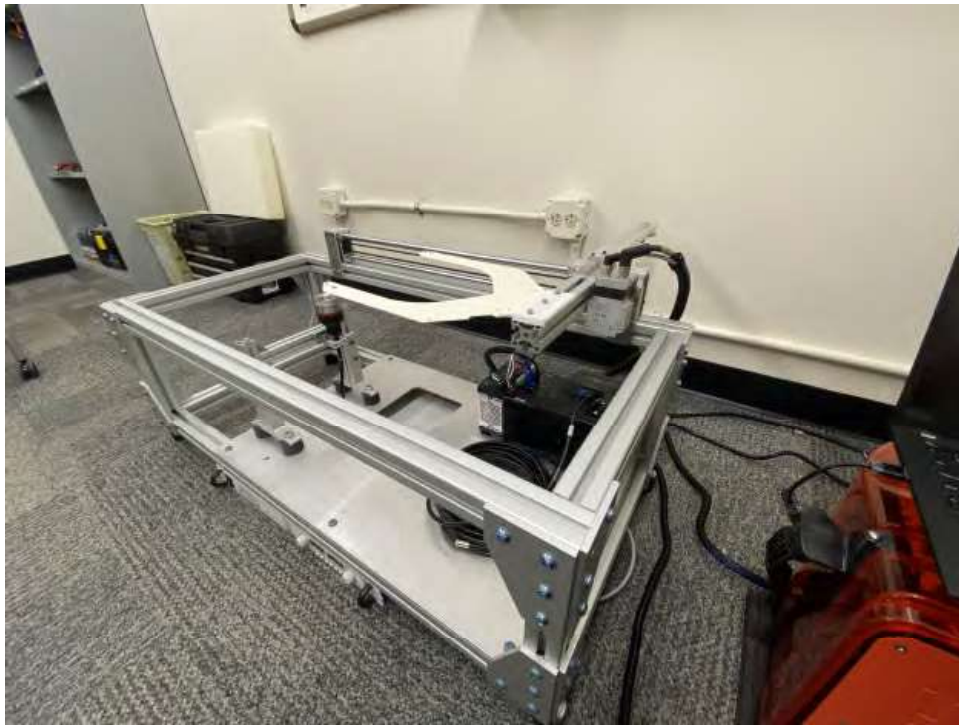
Final System Repeatability

🔄 Future Direction

There is still more to be done before project WASP can be applied to our client's manufacturing processes. As discussed before, 3 sensors would be ideal to more accurately measure complicated surface profiles. The team has incorporated mounting space for additional sensors, but testing would be needed before operational use.

Additionally, the testing section above is meant to demonstrate the necessary steps for any benchtop system. If implemented into a specific industry use-case, there should be adequate vibration, system, and repeatability testing conducted on a recurring basis to ensure accurate data.

Lastly, the conditions of the wafer transfer process utilized by KLA provide some unknowns. This project encountered a range of vibrations which needed to be addressed and this will need to be performed on KLA equipment in order to obtain repeatable and reliable surface profiles.



Conclusion

Project WASP was successful in validating the potential for a single-sensor wafer metrology system. Integrated metrology systems are becoming increasingly essential to quality control for high-tech industries as tolerances tighten and processes become more automated. KLA has been an essential partner to the university and our team, and we hope this project proves helpful to their mission.

Meet the Team



Behruz Rashidov

Project Manager

Behruz managed team goals and schedules to ensure the timely and of quality completion of the WASP project. He also contributed to the design of the linear actuation system and testing. He works as a teaching assistant at CU, and has particular interests in project management and automation.



Jackson Hughes

Logistics Manager

Jackson is the logistics manager, backed by his experience from his business and engineering management minors. Jackson is pursuing a career in technical project development, and has worked on process automation across multiple industries.



Abby Oglesby

Finance Manager

Abby has served as the financial manager for this project. In this role she has benchmarked all technical purchases as well as monitored and maintained the team budget. With experience in energy and STEM Policy development, she aspires to help innovate, progress, and improve throughout a variety of engineering industries.



Nicholas Sanchez Tennis

Manufacturing Engineer

Nicholas was the manufacturing engineer for project WASP. In this role he was responsible for the manufacturing minded design of all the hardware and bringing the designs to life. Nicholas is pursuing further professional development in manufacturing, as well as in CAD and product design and testing.



Summer Andrews

Systems & Test Engineer

Summer was the systems and test engineer for project WASP and is responsible for organizing client and engineering requirements, overseeing testing procedures, and analyzing testing results. Summer is a current mechanical engineering student pursuing a bachelor's-accelerated master's degree, and plans to graduate late 2022.



Sean Connelly

CAD & Software Engineer

Sean was the CAD and software engineer for Project WASP and was responsible for ensuring the completion of a cohesive CAD model as well as developing the Python software responsible for processing the raw data from the sensor array. Sean aims to pursue a career in spacecraft design at NASA's Jet Propulsion Laboratory.



Acknowledgments

KLA+: Thank you for sponsoring this project.

Dr. Harb & Mitch Allen: Thank you for your council, expertise, and support.

Paul Brayford: Thank you for your continuous support, guidance, and expertise in moving this project forward.

Dr. Kotys-Schwartz & Dr. Steinbrenner: Thank you for providing background information, feedback, and guidance to educate and improve our team and project.

Greg Potts & Chase Logsdon: Thank you for helping our team in bringing our project to life.

Program Assistants: Thank you for your consistent communication and assistance with our questions.

Shirley Chessman: Thank you for your assistance with a workspace and support.

Lauren Wheeler: Thank you for helping our team navigate the procurement process.

And you, the reader.