Data-Driven Analysis and Unsupervised Anomaly Detection on Mechatronic Wafer Lifters

Torque Signal Analysis Under Varying Operating Conditions

Graduate

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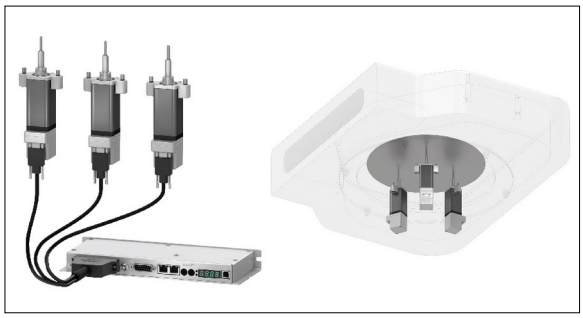
Introduction: The manufacturing of semiconductor devices requires precise and repeatable wafer handling. During processing, wafers are moved between defined positions while the surrounding process conditions can change. For this purpose, VAT Group AG has developed a mechatronic wafer lift system (Figure [1]). The system can operate at pressures ranging from high vacuum to atmospheric pressure and at different temperatures. These conditions can affect the mechanical properties of the system and therefore also the torque required by the actuator during a lifting cycle. The torque measured during a lifting cycle contains information about the mechanical behaviour of the wafer lift system. Changes in pressure or temperature may affect the shape or magnitude of the torque curve. It is therefore of interest to determine whether measurements recorded under different operating conditions show consistent differences and whether these differences are large enough to separate the operating conditions from each other.

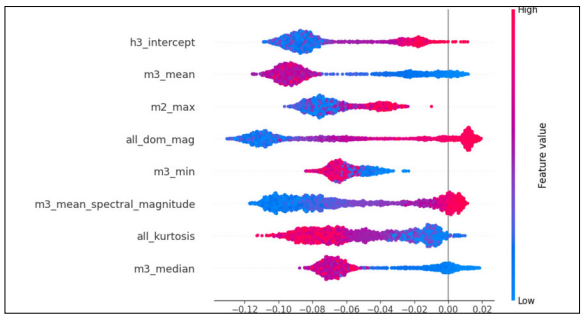
Approach: The recorded torque curves are evaluated using statistical methods to determine how the measurements vary across the investigated conditions. In total, two systems are considered, consisting of six individual wafer lifters. In addition to the statistical analysis, an anomaly detection method is applied. For the anomaly detection, time-domain and frequency-domain features are extracted from different segments of the torque curves. The segmentation depends on the individual motion steps, which include holding phases and motion phases at different speeds. The Isolation Forest is selected as the anomaly detection model. It is an unsupervised machine learning method that uses the extracted features to isolate anomalous observations. In addition, SHAP (SHapley Additive exPlanations) values are used to interpret the features contributing to the detected anomalies and allow a more detailed investigation of the results (Figure [2]). The purpose of this analysis is to investigate whether deviations from a reference behaviour can be detected in the measured torque curves. This provides a complementary approach to the statistical comparison for evaluating changes in the system's behaviour.

Result: The results showed that statistical analysis can reveal differences between the operating conditions and individual lifters. The pressure conditions could be clearly distinguished, as the required torque was higher under vacuum. Differences were also found between the lifter systems, with one lifter set showing more outliers and larger variations than the other. The influence of temperature was less visible in the torque curves and therefore required a more detailed analysis. In general, the measured torque was higher at room temperature than at high temperature. The Isolation Forest confirmed this observation. A model trained on room-temperature cycles classified 98.7% of the 2,274 high-temperature cycles as anomalous. The two most influential features were identified using SHAP values and compared in a scatter plot (Figure [3]). The temperature conditions showed a clear separation, while some overlap remained, but the same lifters still showed consistent differences. Overall, the results indicate that operating conditions can be distinguished based on the torque curves. Additionally, the anomaly scores could be used for predictive maintenance by detecting deviations early and helping to prevent further process escalation and unexpected failures.

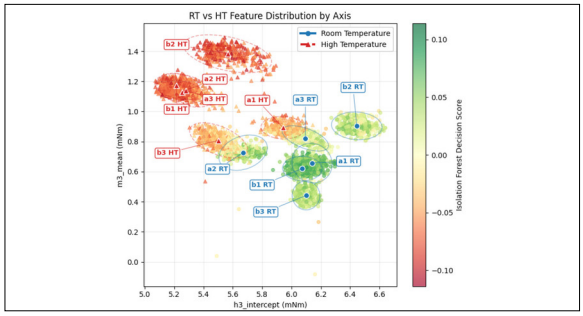
[1] Mechatronic Wafer Lift System and Its Mounting Position.
www.vatgroup.com/series/mechatronic-wafer-lift-system



[2] SHAP analysis of the Isolation Forest trained on room-temperature data and tested on high-temperature data.
Own presentment



[3] The distribution of the two influential features under room-temperature and high-temperature conditions.
Own presentment



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