Fault Diagnosis for High-Tech Precision Mechatronics: With Application to a Prototype Wafer Stage

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The productivity of high-tech production equipment largely determines its economic value, and unexpected malfunctions can lead to a major loss of productivity. These malfunctions may arise from defects, aging, and wear of system components. To minimize equipment downtime, critical faults should be detected and addressed early through predictive maintenance, which involves predicting and detecting faults in equipment and pinpointing their origin. This is the process of Fault Detection and Isolation (FDI).

Before a machine is commissioned, models of the system are typically available through Finite Element Modeling or identified models during system integration. However, after control design and system integration, these models are often left unused. By creating a digital counterpart of the system that is informed with real-time data from a large number of sensors and actuators, the valuable underlying physical model can be exploited. This model allows to isolate the origin of the anomalous behavior, enabling effective self-healing or targeted and eficiently scheduled hardware maintenance [1].

This work presents a fault diagnosis system, based on an accurate low-order Multi-Input Multi-Output (MIMO) modal model. The digital counterpart for fault diagnosis is synthesized by means of a numerically reliable nullspace-based FDI approach [2]. It is shown that effective fault diagnosis filters can be synthesized which solve the fault detection and isolation problem. By means of an experimental validation on a next-generation prototype wafer stage, see Figure 1, its effectiveness is illustrated. The fault diagnosis system guarantees fault detection and isolation of a large number of imposed actuator and sensor faults. In addition, an effective self-healing mechanism is presented where the role of failing actuators or sensors is distributed over the healthy components. The proposed approach, involving data-enriched physics-based models, is applicable to a large range of systems, including production machines and scientific instruments.

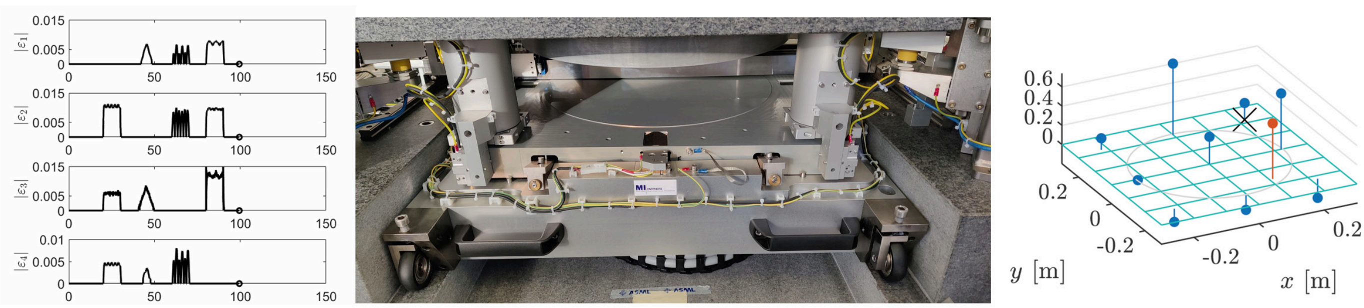

Figure 1
Results when applying the fault diagnosis systems in real-time on a MIMO prototype wafer stage (center). The system contains a large number of actuators and sensors which can go faulty. The stage follows a higher-order reference trajectory and is controlled through modal control. A large number of faults are considered for the fault diagnosis filter design, i.e., one fault per actuator or sensor. Faults are applied at different time instances and are isolated using residual signals (left), which are sensitive to the faults. A digital representation, i.e., a digital twin (right), of the stage is shown where the isolated rootcause of the fault, at this time instance the actuator marked with (X), is highlighted in real-time and the surrounding actuators compensate for the faulty actuator.

REFERENCES

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