Digital Twins for Precision Mechatronics:

Predictive Maintenance via Fault Detection and Isolation*

Koen Classens[1], W.P.M.H. (Maurice) Heemels[1], Tom Oomen[1]

[1]Eindhoven University of Technology, The Netherlands

K.H.J.Classens@tue.nl

Abstract

Despite excellent system design and major advances in control theory, the condition of high-tech production equipment deteriorates over time, making maintenance unavoidable. Effective, targeted, and optimal timing of maintenance is of paramount importance due to the high costs associated with downtime. In particular, unexpected downtime due to failure is expensive and should be minimized. This maximizes the economic value as it is predominantly determined by productivity. To minimize downtime, predictive maintenance is an effective strategy for which real-time fault diagnosis systems serve as foundation. Real-time fault diagnosis is pursued via the process of predicting and detecting faults and simultaneously pinpointing its origin, which is called Fault Detection and Isolation (FDI).

Generally, FDI systems are either data-driven or based on physical models. As next generation FDI system, a physics-based model is envisaged which is learned from data to improve the predictive capability of the digital counterpart, see Fig. 1 for an overview. Models of the system are typically available prior to commissioning a machine, for instance, through Finite Element Modeling or identified models during system integration. After system integration and control design, the model is generally left unused. Evidently, this model is valuable and can be exploited in the form of a digital twin that is

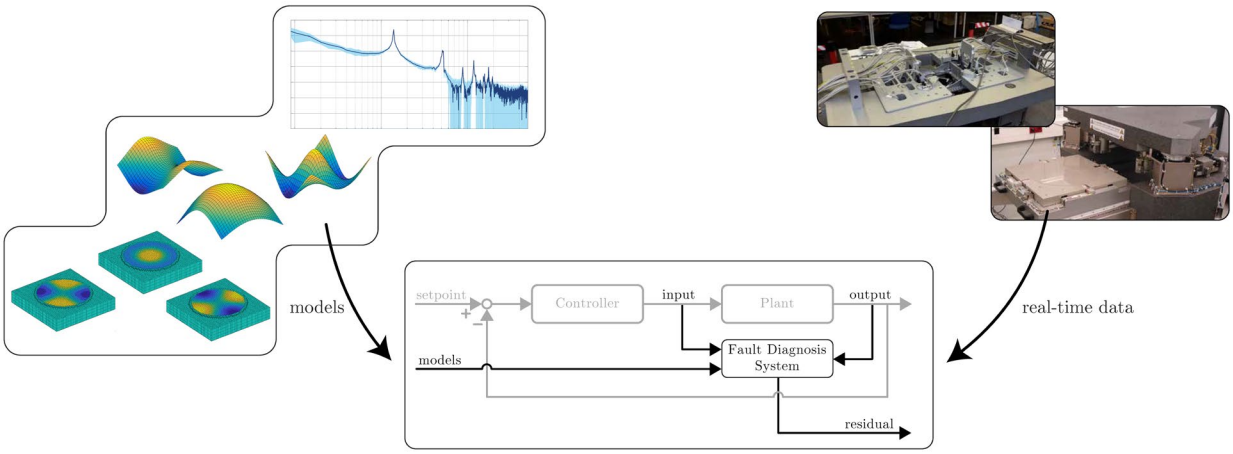

Figure 1. Real-time data of a large number of actuators and sensors can be used jointly with physical models for fault diagnosis filter design.

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informed with real-time data through a large number of sensors and actuators. Comparison of this digital counterpart to the physical plant allows to monitor the ageing of critical components and allows to detect anomalies at an early stage. The underlying physics enable to isolate the origin of anomalous behaviour, which in turn allows for effective self-healing or targeted hardware maintenance.

An experimental multi-input multi-output setup has been developed which exhibits dominant flexible behavior and resembles a next generation motion system, see Fig. 2. A fault diagnosis system has been developed, operating in real-time, which allows to effectively detect faults and pinpoint its origin.

The developed approach consisting of data-enriched physics-based digital twins is general in nature. The proof-of concept demonstrates that the approach can be applied to a broad industrial range of mechatronic systems including production machines and scientific instruments. In this way, the present research project focuses on bridging the gap between data-based and model-based FDI approaches, which are currently largely separated.

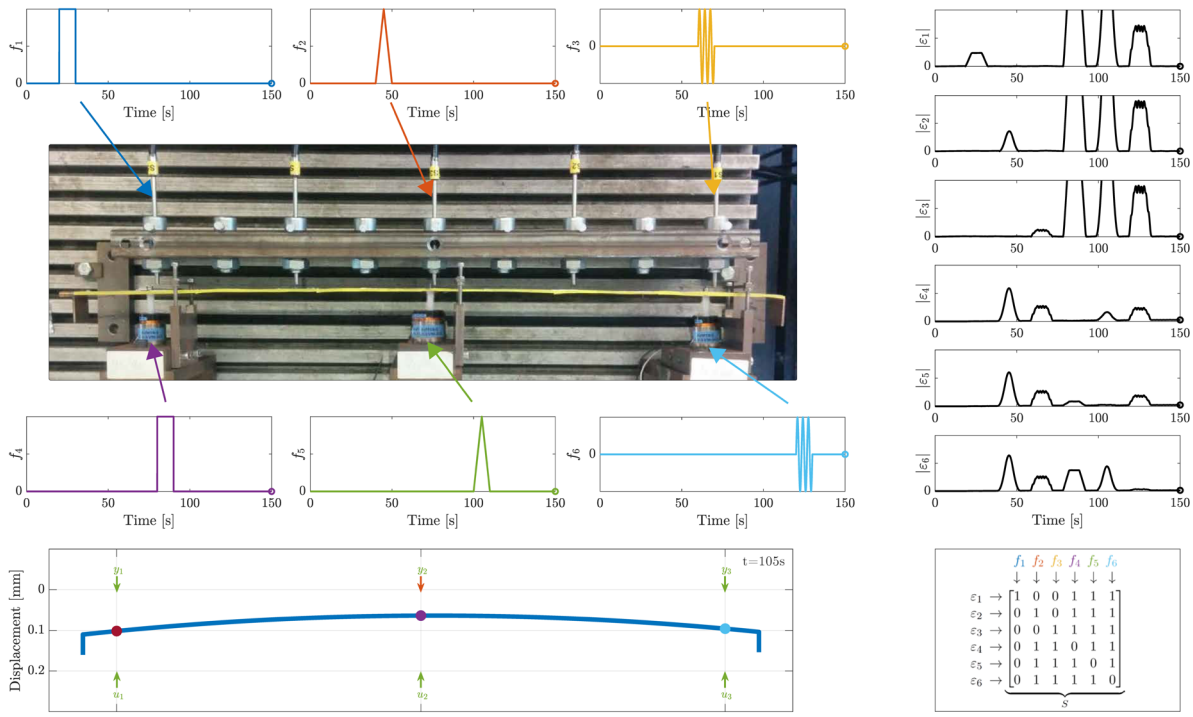

Figure 2. Results when applying the fault diagnosis systems in real-time on a multi-input multi-output prototype flexible beam setup. The system consists of the beam (equipped with yellow tape), three voice coil actuators, and five sensors of which three are used. The beam follows a fourth-order reference trajectory and is controlled through modal control. Six additive faults are considered for the fault diagnosis filter design, i.e., one fault per actuator or sensor. Faults are injected at different time instances and are isolated using the six residual signals, ε_1 to ε_6, which are sensitive to the faults according to the structure matrix S. On the bottom left a digital representation, i.e., a digital twin, of the flexible beam is shown at $t = 105$ s. The isolated rootcause of the fault, at this time instance sensor 2, is highlighted red in real-time.

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