Abstract

In the Industry 4.0 era, an increasing quantity of time series data is collected from various real-world applications including, for example, healthcare, finance, weather forecasting, astronomy, manufacturing, reliability engineering. The motivation behind the present Ph.D. thesis work is Prognostics and Health Management (PHM) which is an interdisciplinary field of research and application aiming at detecting the degradation onset of industrial equipment, diagnosing its faults, predicting its Remaining Useful Life (RUL) and proactively managing its maintenance to improve system safety, availability and reliability. PHM requires monitoring a large number of equipment parameters to evaluate the health state of the equipment. The monitored parameters of practical interest are typically non-nonstationary time series, i.e., their statistical and frequency characteristics change with time. This is due to the fact that the monitored parameters are influenced by the environment in which the equipment operates, which is typically evolving as time passes, and by the equipment degradation which is an irreversible process which typically causes monotonic trends on the parameters. Another difficulty of PHM is that the information on the true equipment degradation level is not available in many applications due to the cost of its estimation. As consequence, the available data are incomplete, right-censored time series. These issues in PHM have motivated the development of time series analysis methods with following research objectives: *I*) development of an anomaly detection method for non-stationary time series; *II*) development of a classification scheme for non-stationary curves and *III*) development of a similarity-based regression method for time series prediction in presence of incomplete data. From a PHM perspective the three research objectives correspond to fault detection, fault diagnostics and fault prognostics, respectively. To achieve these objectives, we have considered wavelet and instance-based (also known as similarity-based) methods.

With respect to research objective *I*), we have developed a novel method for sensor data validation based on the analysis of data regularity properties through the joint use of Continuous Wavelet Transform (CWT) and image analysis. Anomaly detection is performed by comparing the similarity between the CWT scalogram obtained from the test signal with those obtained from historical data in nominal condition with a fixed threshold. The developed method has been successfully applied to temperature signals from a reactor coolant pump. Differently from the typical sensor data validation methods which detect sensor malfunctions by observing variations in

the relationships among measurements provided by different sensors, the proposed solution can be systematically applied to a fleet of plants, without requiring sensor grouping.

With respect to research objective *II*), we have developed a novel Functional Data (FD) based Empirical Classification System (ECS) for diagnosing the degradation level of industrial equipment. The developed ECS combines wavelet smoothing, elastic registration and LASSO multinomial logistic regression. The proposed method has been successfully applied to case studies concerning solenoid valves mounted on train braking system and knives used in the packaging industry. The proposed solution which, at the best of our knowledge, is a novel approach in fault diagnostics, is shown to allow improving the classification performance with respect to traditional approaches of the PHM field.

Finally, with respect to research objective *III*), we have developed a novel direct RUL algorithm capable of exploiting the information provided by incomplete, right-censored degradation trajectories for effective RUL prediction and quantification of its uncertainty. The novel developed method combines similarity measure with Dempster-Shafer evidence theory. Its application to two case studies concerning turbofan engines and cutting tools used in the manufacturing, has shown that it provides more accurate RUL predictions in comparison with a similarity-based regression method of literature. Furthermore, the proposed method allows properly quantifying RUL predictions uncertainty.

The obtained results show that the developed time series methods can be effective in PHM industrial applications and can support the development of condition-based and predictive maintenance strategies.