Condition-Aware Systems: Towards Real-Time Health Monitoring of Unmanned Vehicles

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ABSTRACT

This paper presents an overview of the technologies and computational strategies that we are developing at Politecnico di Torino to move most of the vehicle health monitoring from offline to online, real-time execution. This will ease the wide adoption of unmanned vehicles in critical operational scenarios, by improving their availability and their mission reliability. Our research addresses the sensor technologies to acquire the data necessary for health monitoring, and the computational strategies required to process such large amount of data in real-time. Our tests showed promising results, suggesting the feasibility of a robust, real-time UxV health monitoring system.

1.0 INTRODUCTION

Operational scenarios for military vehicles of the future require the extensive interaction of different systems to happen in real time to meet the objectives of the mission. This motivates the particular attention dedicated to the characterization of the interacting systems in terms of readiness, responsiveness and operational capabilities, which drives the development of devices equipped with varying autonomy/intelligence levels to support, integrate or replace human intervention. A critical element for the success of the mission is that autonomous vehicles (UxVs) employed in integrated operational scenarios can reliably cope with failure without jeopardizing the success of the mission. Therefore, determining and characterizing the reliability properties of these systems is of critical importance, and yet presenting a variety of challenges.

Novel approaches to reliability-based maintenance of UxVs adopt advanced prognostics strategies to promptly identify incipient faults and failure modes (diagnostics), and estimate the corresponding remaining useful life (prognostics) as a measure of the system's availability, readiness and responsiveness in the operational environment. Within this context, our goal is to move the entire diagnostics and preliminary prognostics onboard in support of a timely and intelligent decision making on maintenance planning and intervention. Two main technology areas can be identified as the key elements for the development of this kind of intelligent vehicles: sensing technologies (Cheng et al, 2010, and Guan et al., 2020) and artificial reasoning (Conroy et al, 2018, and Oluwasegun and Jung, 2020). Our research activity is progressing along both these trajectories: on one hand we are developing hybrid physics-based and data-driven artificial reasoning for real time diagnostics and prognostics; on the other hand, we are demonstrating the use of fibre optics sensors for health monitoring applications on small scale UAVs.

Fibre Bragg Gratings (FBGs) are optical sensors that combine minimal intrusiveness with high measurement resolution and high-density installation, with marginal impact on vehicle weight and power budgets. We are testing FBG-based sensor networks for multifunctional use on UAVs including (1) virtual sensing of actuator loads, (2) structural health monitoring and (3) assist inertial measurements.

A major challenge for real-time fault diagnosis and failure prognosis is the uncertainty arising from multiple sources: the measurements, the behaviour of numerical models with respect to the physical systems, and the inherent variability in the wear rate of components. We are developing artificial reasoning tools to be integrated in a Prognostics and Health Monitoring (PHM) framework able to deal with and quantify the uncertainty of reliability boundaries. This paper provides an overview of our work on the development of FBG based sensing technologies and computational strategies for aerospace applications. Particular attention is dedicated to real-time reliability assessment of on-board actuation equipment, in-flight load characterization and condition monitoring of UAV systems and structures.

In the remaining of this paper, Section 2 discusses the sensing technologies we are developing and testing at Politecnico di Torino for health monitoring of structures and systems; Section 3 provides an overview of the computational strategies that we have been developing to enable the real-time execution of the entire health monitoring process.

2.0 FIBER-OPTICS SENSORS TO ENABLE HIGH-RESOLUTION IN-FLIGHT MEASUREMENTS

A key element to enable efficient on-board condition monitoring strategies for unmanned vehicles is the availability of accurate, robust and widespread measurements of the system operating parameters. The sensing technologies needed for these kinds of applications shall feature high integrity and minimal intrusiveness. The measurements need to be robust to external disturbances, highly reliable, and the sensors are required to be installed in large quantities without excessive impact at vehicle level. In addition, the installation of any additional sensor, other than those required for the nominal operation of the vehicle, shall minimize the complexity introduced in the system and shall not significantly affect the overall failure rate.

Fibre Bragg Gratings (FBGs) are optical sensors that leverage a periodical modulation of the refraction index in the core of an optical fibre to act as a selective mirror for a specific wavelength, proportional to the period of the grating. As the fibre is subject to thermal or mechanical deformations, the reflected wavelength drifts accordingly and permits to measure temperature and strain. FBGs are minimally invasive and can be easily multiplexed, as tenths or hundreds of sensors can be contained within a single optical fibre. On an autonomous vehicle, many applications can take advantage of an on-board FBG-based structure monitoring system. The position and extent of damages in composite structures can be inferred from local measurements of strain, and permits to estimate the residual capability of the structure; our research suggests that accurate and timely assessments of the structure health can be obtained with a low computational effort (Mainini and Willcox, 2017). The same information is very useful for actuator health monitoring: as direct measurement of actuator loads is usually infeasible or impractical, we are looking into reconstruction of loads from the distributed sensing of the airframe strain field: a reliable estimate of the actuator load is necessary to estimate the health condition of flight controls in real-time (Berri et al, 2020). Eventually, the strain field measurements can be leveraged to reconstruct the accelerations acting on the structure, to assist inertial measurements for guidance and control applications.

We are currently flight testing a structure monitoring system based on optical sensors for a small unmanned aircraft (Figure 1). This system is a demonstrator for how to embed FBG-based sensing technology within small-scale and medium-to-low cost autonomous vehicles, with strict constraints in terms of weight, power, and computational resources. At the same time, it offers the capability to measure the strain with high accuracy and repeatability, in several tenths of key locations across the airframe. The measured data is transmitted to the ground station in real-time, and allows to obtain an estimate of the aerodynamic loads on the flight control actuators.

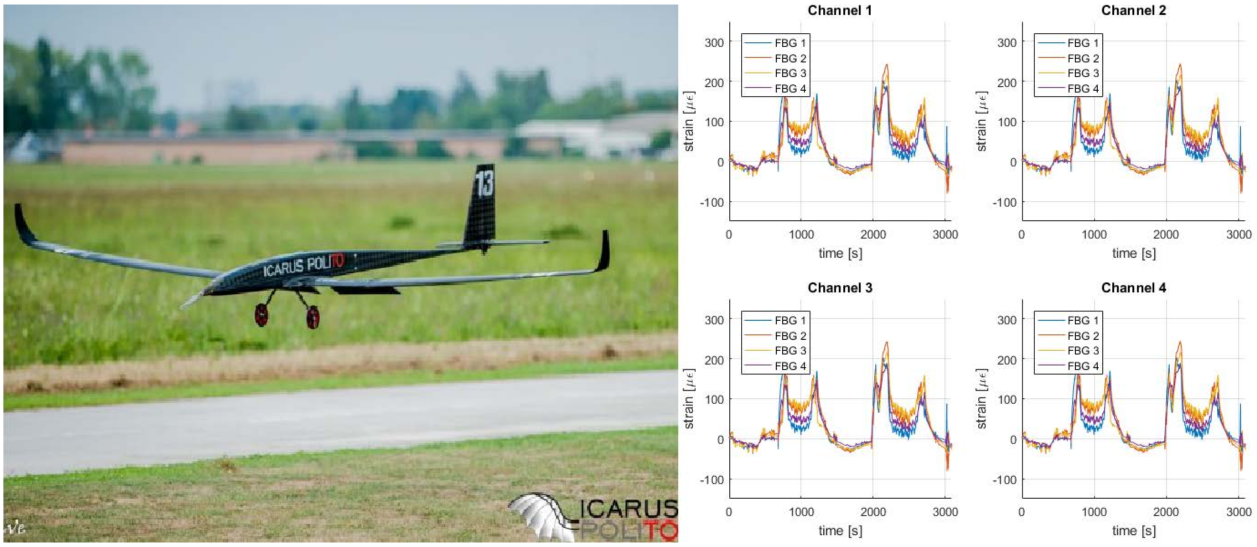

Figure 1: Left: flight test of the UAV platform equipped with the FBG-based structure monitoring system. Right: strain data acquired from the test

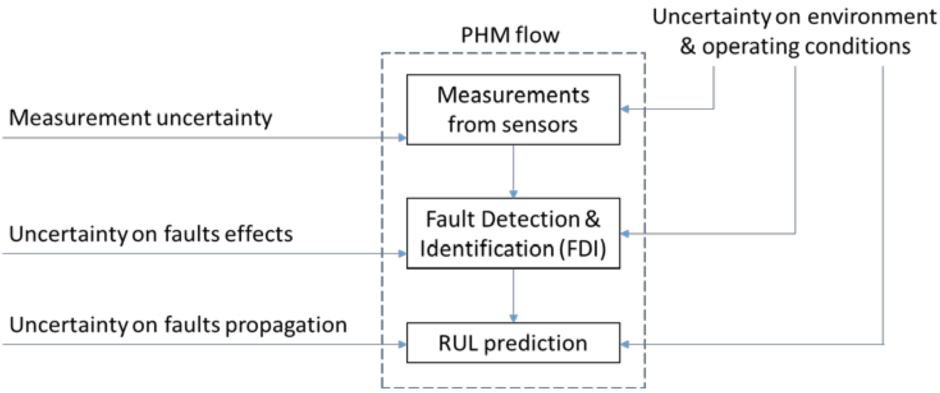

Figure 2: Schematic representation of how the different uncertainties interact with each other across the health monitoring process.

3.0 ARTIFICIAL REASONING TO DEAL WITH UNCERTAINTY SOURCES

Any prognostic strategies for the fault diagnosis and failure prognosis of a complex engineering system must deal with the multiple sources of uncertainty that affect the prediction of remaining useful life. Figure 2 illustrates the uncertainty components that may affect the overall health monitoring process. Those components are rarely independent, but rather interact and act in a combined manner, and propagate along all the steps of the health monitoring process. In particular, the hardware sensors installed on the system are characterized by their finite accuracy, resolution and repeatability. The models that describe the behaviour of the system under the effect of faults and those that describe the propagation of damages are affected by structured uncertainty (i.e. that associated with the model parameters) and unstructured uncertainty (i.e. the simplifying assumptions made while building the models). These propagate to the diagnostic and prognostic tasks, affecting the estimates of the system's health. In addition, the uncertainty contributions associated with the specific operating scenarios and mission environments further widen the dispersion of performances delivered by each individual component: equipment exposed to harsher conditions will fail prematurely, and this behaviour has to be accounted for by prognostic strategies.

Our approaches to fault detection and failure prognosis are designed to deal with the sources of uncertainty throughout the PHM process. We developed an original framework that combines unsupervised machine learning and projection-based model order reduction to compress the relevant information from sensor measurements, reduce the dimensionality of the fault detection problem, and minimize the amount of misleading information introduced in the subsequent computations. This making it possible to use supervised machine learning for fault detection in an effective and efficient manner. In particular, we observe that an accuracy of a few percent of the actual fault parameters can be achieved with computational time of the order of milliseconds with computing resources typical of a common laptop.

Particular attention has been dedicated to the specific problem of health monitoring of electromechanical flight control actuators. We have been working on novel computational strategies to learn from real-time measurements and signal acquisitions.

Regarding the failure prognosis task, we propose to combine elements of reinforcement and transfer learning with dynamical estimator filter, to obtain in real-time models describing the damage propagation rate uniquely from the observations of the physical system, without requiring prior, uncertainty-prone knowledge about the reliability characteristics of the vehicle and its subsystems. Our particular method allow to assimilate measure date in an efficient and informative manner. We demonstrated that the proposed methods deal efficiently with the fault detection and RUL prediction tasks, demanding few computational resources, and promptly adapting to unpredictable changes in the operating conditions of the monitored equipment (Berri et al, 2021). Figure 3 compares the predicted and actual RULs of a system. In the top graph, the propagation of faults is uniform; in the bottom one, an unpredictable event increases the damage propagation rate, and the algorithm is able to adapt its prediction shortly after, by assimilating additional information from the physical system.

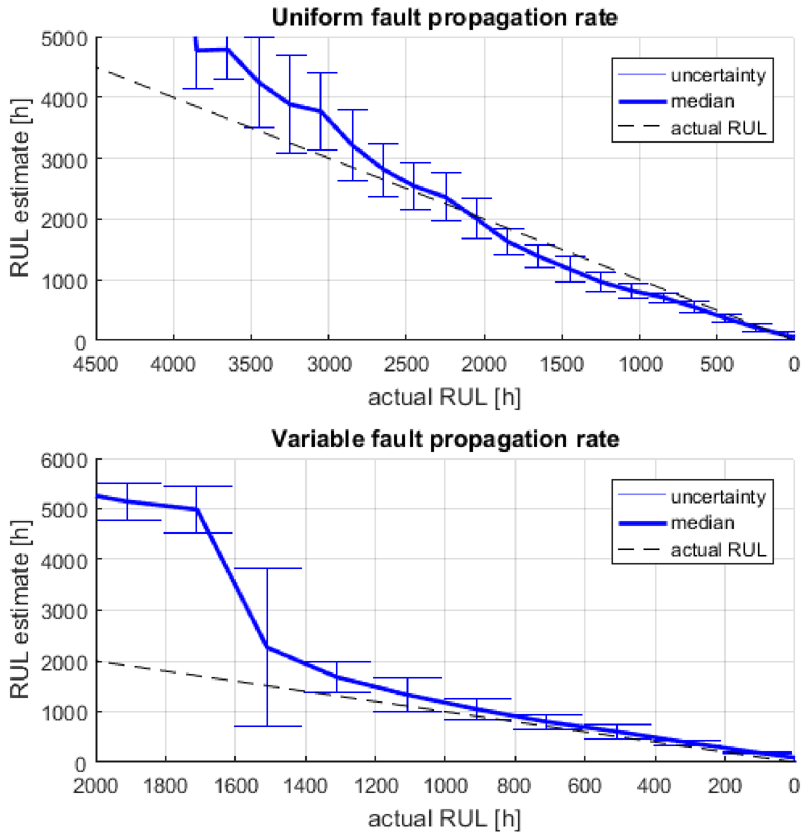

Figure 3: Comparison between the actual RUL of the monitored system and the estimate predicted by the failure prognosis algorithm. Top: the propagation of damages is uniform throughout the lifecycle of the system. Bottom: an unpredictable event at RUL=1800h increases the damage propagation rate.

4.0 CONCLUSIONS

The technologies discussed in this paper aim at increasing the health condition awareness of unmanned systems and improving their availability and mission reliability. In particular, we demonstrated the use of optical sensors for the determination of aerodynamic loads on the structure and flight control actuators of UAVs. In addition, our computational strategies real-time prediction of Remaining Useful Life can adaptively inform the planning of maintenance interventions tailored onto the actual condition of the system.

Our current research points toward the integration of the different sensing and computational technologies being developed into a comprehensive framework to support the whole condition monitoring process of unmanned systems, from measurement of physical data to decisions affecting the mission and maintenance planning.

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