Techniques for effective virtual sensor development and implementation with application to air data systems

Summary of the PhD Dissertation: Techniques for effective virtual sensor development and implementation with application to air data systems

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Between 2018 and 2019, two accidents with fatal results happened due to technical reasons on the Boeing 737 MAX 8. Although the catastrophes were related to multiple causes, the core was a fault on the sensor with the task of measure the angle of attack. Several alternatives have been studied during the last 50 years but, though a huge literature exists on the subject, most of the technological solutions proposed by researchers didn't go further TRL 5. These alternatives can be found in literature as virtual sensors or synthetic sensors and they are studied to be applied in the analytical redundancy framework or as primary sensor in a more forward-thinking design.

At the time of writing this dissertation, another revolution is happening in the aeronautical industry related to inhabited and autonomous vehicles. This phenomena worth 19.3 billion $ in 2019 with a Compound Annual Growth Rate of 15.5 % between 2019 and 2025, resulting in 45.8 billion $ in 2025. The design of this kind of platform has some peculiarities, such as the high demand of innovative avionics involving autonomy and usage of COTS components driven by the fast development of the market itself. These aspects result in difficulty in fulfilling the SWaP requirements. An example of critical system that introduces an high number of components is the ADS. Unfortunately, a method able to meet the redundancy required by aeronautical regulations for the ADS is still not ready at the time of writing this dissertation. In fact, nevertheless of the number of studies on the topic of virtual sensors, the hardware redundancy is the unique solution for the above-mentioned safety-critical systems. However, the hardware redundancy might be not suitable for the UAV and UAM fields.

The main reasons behind this slow transition between research and industrial application of synthetic estimation must be searched in the approach used to design the synthetic alternatives of the physical probes. The ideal estimator does not exist and the available alternatives cannot be compared between each other. To respond to the market needs, a basis for comparison must be provided. The approach proposed by this dissertation is inspired by the one followed in the case of traditional sensors: the definition of a design process based on a shared definition of the uncertainty of the sensor. Unfortunately, those metrics have never been proposed in the past so this dissertation sets a first case of common definition. In fact, the results showed in literature focus on the analysis of the error timeseries and sometimes on some other global metrics as the mean error. This approach has some flaws that are described in this work.

At the beginning of this project, the main aim was the practical implementation of the virtual sensor called Smart-ADAHRS, which showed higher uncertainty when working with flight data than with simulated data. This dissertation hence proposes a set of techniques to design and optimize the performance of a synthetic sensor. In this particular case the core is a neural network, hence some of the proposed methods focus on the training of the network. Moreover, the findings in the neural network field given in this dissertation, as the TS analysis or the derivation of the Jacobian and Hessian matrices, are general and they are not limited to the case of Air Data estimation.

The dissertation starts with a detailed definition of the air data, followed by the literature review of the field of synthetic estimation. The mathematical aspects of the problem of estimation of the aerodynamic angles are described together with the description of the ill-posedness of the problem. A chapter is dedicated to the theoretical aspects that can help to move from the preliminary design of the virtual sensor to the tuning of the results. In the same chapter, the formulations for the Jacobian and Hessian matrices of a feed-forward MLP are derived. The experimental setup is described in a dedicated chapter followed by the proposed method of analysis and data augmentation. The final comparison shows the improved homogeneity of the uncertainty, which can be lowered to some degree for the angle of attack. The sideslip angle is also discussed, although the uncertainty due to the experimental setup reduces the confidentiality of the reference.