

## 論文の内容の要旨

論文題目    A Multifidelity Simulation Framework for Digital  
Twin Modelling of Spacecraft  
(宇宙機のデジタルツインモデル化のための  
複数忠実度のシミュレーションフレームワーク)

氏    名    コンタクソグル   アナスタシオス

In Chapter 1, the research motivation is stated, the issues in the industry are presented and the requirements of a framework that satisfies industry's needs discussed. In space, where human intervention is not possible, faults must be autonomously detected. The state of the satellite should be continuously monitored, to both react and notify the on-board health management system. However, inaccuracies, delays, or disturbances can cause component breakdowns that can lead to catastrophic failures. Considering this, a dynamic system simulation can greatly enhance the operational phase of a satellite.

A major cause of inaccuracies is unmodelled physics. A multitude of factors are necessary to understand the thermal profile of the satellite. For example, incoming radiation from a thermal radiation source, e.g., the Sun, heats in a larger degree the surface facing it, compared to the dark side, with the hot side losing more momentum than the cool side, therefore the local temperature is affected by attitude. Additionally, power components release heat, increasing the temperature of surrounding components.

An approach to solving these issues is the Digital Twin. My motivation is to transcend the silo mentality in modelling, which has high accuracy requirements, and put together a framework that can potentially assist in the construction of a Digital Twin and particularly by introducing multifidelity modelling. The focus is especially on spacecraft due to the unique challenges introduced by the space environment, but this research is

by no means restricted to one particular application. The outline of the thesis is also included.

Chapter 2 discusses the necessary concepts and their literature review required for understanding this thesis. These include, multifidelity modelling, cokriging, and the linear and nonlinear methods the multifidelity framework will be compared to, namely autoregression, Gaussian processes and neural networks. Current multifidelity modelling methods are surveyed. In particular, two approaches are used: a multifidelity approach that combines a computationally cheap, low fidelity surrogate model, with an accurate high-fidelity model. In the case of the former, recurrent neural networks, particularly a Gated Recurrent Unit is considered. For the latter, a finite element model is used to produce sparse high-fidelity data describing the satellite's state.

Special attention is given to cokriging, also known as Multifidelity Gaussian process regression, which is a popular surrogate model for geospatial applications. Fundamentally, cokriging is a weighted combination of a low fidelity kriging model and the difference between low and high-fidelity models. For example, finite element data is expensive to generate. However, abundant low fidelity data could be taken advantage of to speed up the process. By means of cokriging, low fidelity data is corrected by high fidelity data through a comprehensive correction, where the parameters are given using Gaussian processes to provide uncertainty quantification. When new data arrives, the model can be refitted for a minimal computation cost.

Chapter 3 discusses the concept of the Digital Twin. Initially, Digital Twin was treated as a high-fidelity model or multidisciplinary simulation, and the real time component had not yet been under consideration. However, the definition has evolved to encompass dynamic modelling and bidirectional communication and mapping to the physical system. In essence, the Digital Twin is based on the simple idea of linking a physical object with its digital counterpart accurately and in real time. However, a fit-all concept architecture has not been developed,

The difference between model (physics) based and data driven methods and their combination, or hybrid models is also discussed. Emphasis is given on what different sources of information offer to simulations. Finally, the literature on Digital Twin in the context of Aerospace is discussed and the gaps in research are presented.

In Chapter 4, the multifidelity framework to be tested in this thesis is presented. It

applies the concept of dynamic Digital Twins which includes bidirectional communication and mapping to the physical system. Emphasis is placed on handling a constant stream of live data and cokriging estimators. These estimators leverage multiple separate estimations, of varying fidelities, for a quantity of interest, and provide a better approximation compared to traditional regression methods that often treat data as spatially independent observations.

The multimodal aspect of said framework is also discussed. The ways the framework can be applied to satellite are considered and finally the methodology which will evaluate the framework's robustness is analysed.

Chapter 5 contains the experimental part of the thesis. After an introduction and metrics description, four experiments are discussed. The multifidelity framework is demonstrated using thermal data from two satellites. A) The ISSL6U-1 satellite, a non-Japanese 6U cube satellite, co-developed by the Intelligent Space Systems Laboratory (ISSL) of the University of Tokyo, intended to orbit in Low Earth Orbit (LEO) and is intended to provide a convenient validation platform to test optical sensors. B) The SDS-4 (Small Demonstration Satellite 4), a small 5U satellite developed by JAXA. It was launched as a secondary payload on the Shizuku mission in 2012 and its purpose was to conduct experiments on-board.

Thermal and simulated power data is used to demonstrate the multimodality of the approach. The multifidelity framework is benchmarked against traditional approaches and the ability for real time simulations is investigated by using the sliding window technique. The experimentation in this study produced promising results.

In the final chapter, the work is summarised, and its limitations are discussed. The framework shows consistently better accuracy across all simulations against the GRU and better or similar against the Gaussian process and ARIMAX. However, drawing information from multiple sources, the multifidelity framework is more robust than Gaussian processes to noisy data and missing values. The multifidelity framework is more costly than both the GRU and the Gaussian process, however it is less computationally intensive than ARIMAX. The multifidelity framework showed consistently better performance than the other methods. Finally, the contributions are stated, and future research is proposed. Final remarks and conclusion.