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Machine learning based health monitoring for highly reusable launch vehicles

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Reusable Rocket Engines

The complexities involved with the reuse of rocket engines was first experience with the operation of the Space Shuttle Main Engine (SSME). Early within its operational life, it was realized that maintenance activities had a major impacted the costs and availability of the Space Shuttle. The importance of an integrated approach of health monitoring and maintenance was identified, and advance sensing techniques, data processing and maintenance methods would be developed. Although the Space Shuttle program was cancelled in 2011, many lessons were learned for the next generation of reusable rocket systems.

Perhaps the most striking lesson from the SSME is that the success of a reusable system starts with a design not solely optimized for performance, but which trades of performance and reusability. A reusable design should account for damage limiting operation, health monitoring, inspectabilty and maintainability.

Influence of Recovery & Maintenance costs

Based on their experience with the SSME, Cannon et al. indicated that the operations costs, which include maintenance, were nine times higher than the acquisition costs, which included R&D [1]. A significant source of costs was due to the large number of personnel required for inspection and maintenance efforts, which took up to 120 hours per turn around. It part, this was due to the non-automated, and non-integrated nature of the process.

More recently, a economic analysis by CNES showed the relative influence of recovery and refurbishment costs for reusable launch vehicles versus other factors such as fixed costs, percentage reuse and launch rate [2]. (See fig. 1). Here it is seen that recovery and refurbishments costs have an impact of comparably magnitude to fix costs and percentage reuse, due to which it can be expected to be one of the key sources of competitive advantage in the future.

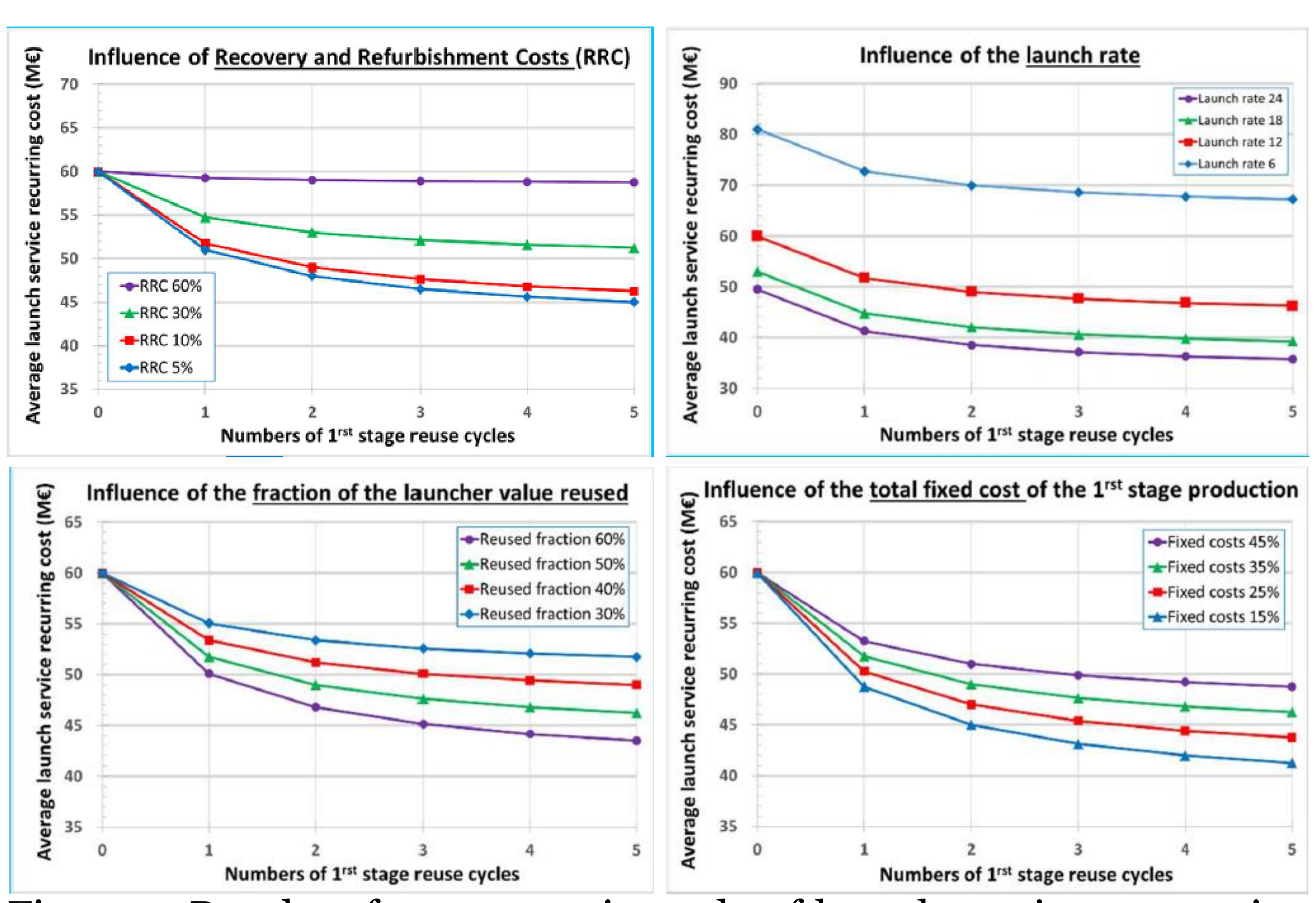

Figure 1: Results of a parametric study of launch service costs using reusable vehicles by CNES [2]

Holistic Approach to Reuse: Integration of Control, Health Monitoring & Maintenance

An integrated approach to reusability aimed at economic profitability of the launch service would address maintenance at various stages of the project life cycle. In the design phase, the expected part life has to be seen in light of the foreseen system life. Parts that are expected to need active maintenance or replacement during the system life will need to be accessible, such that maintenance times can be limited. The control and health monitoring system can be integrated to facilitate damage reducing flight operations, as well as onboard, fault detection, part life assessment and maintenance planning. That is, the system would aim to reduce damage where acceptable to the mission, and gather information in real-time of the damage induced to critical components. The latter would allow ground personnel to focus maintenance activities, and prevent unnecessary disassembly and reassembly.

To this end, knowledge of the failure modes of reusable launch systems are necessary, and advanced sensors and data processing methods will be necessary to detect problems, assess part and system life and pre-process this information to facilitate maintenance activities.

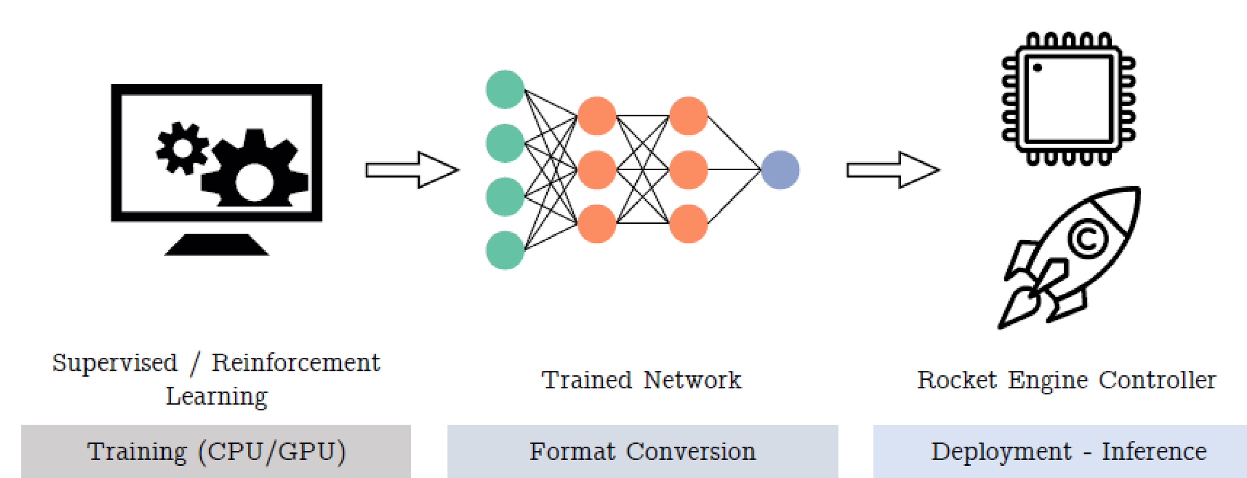

Figure 2: Diagram of the incorporation of machine learning algorithms in space launch system by DLR [3]

Sensors

In addition to common sensors such as pressure gauges, thermocouples, RTDs and accelerometers, advanced instrumentation will need to be developed to asses processes in propulsion systems that may have an effect on system health over multiple flight cycles. For instance, the deposition of solid carbon following thermo-catalytic decomposition of fuel in cooling channels, will cause increases in wall temperature. Using suitable sensor arrays, such effects can be detected even before damage to the engine walls is incurred. Selecting the necessary sensors depends on knowledge of common failure modes, as well as new ones that may only present themselves after several flight cycles.

Machine Learning

Different Machine Learning techniques have been successfully applied to relevant areas such as thermo-mechanical analysis of engine cooling channels and fatigue life predictions. [3]. Trained algorithms can deliver the accuracy of CFD and FEM solutions at a fraction of the computational cost and time. However, the quality of the system depends on the training approach and available data.

Sweden's opportunity

Although academia and industry have been working on key technologies and methods for such system, an **integrated approach or system has yet to be demonstrated** (in open literature). While the space launch market is continuously growing, expertise in the development and use of integrated health monitoring and maintenance systems will present a growing financial asset. In Sweden, the necessary competences to develop such a system, including vehicle and propulsion system design, sensor development and machine learning, production technology etc. are available in industry and academia at this time. Therefore, **an opportunity exists** at present to start development of intellectual and industrial assets that facilitate **Sweden to benefit in a sustained** way from the growing space business.

[1] I. Cannon, A Norman, and M. Olsaky, Application of SSME Launch Processing Lessons Learned to Second Generation Reusable Rocket Engines Including Condition Monitoring, AIAA/ASME/SAE/ASEE 24th Joint Propulsion Conference, July 1988
[2] J. Oswald, K. Kheng, L. Pineau and J. Bahu, Economic Analysis of a Semi Reusable Launcher for Europe, 71st International Astronautical Congress, IAC-20-D-2.2.4, October 2020
[3] G. Waxenegger-Wilfing, K. Dresia, J. Deeken and M. Oschwald, Machine Learning Methods for the Design and Operation of Liquid Rocket Engines – Research Activities at the DLR Institute of Space Propulsion, Space Propulsion 2020+1 Conference, 2021.