

Application of Model-Based System Engineering to a planetary rover design

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Abstract—Traditional system engineering methods have shown their limits when applied to highly complex systems such as rovers. In parallel, the digitalisation of the industry and the democratisation of the use of models in engineering force the system engineering field to adapt and change its practices by adopting a new approach: Model-Based System Engineering. This project aimed to provide a comprehensive example of an MBSE approach applied to a planetary rover design case study. The MathWorks MBSE toolchain is used to reverse engineer the NASA Sojourner rover. As a result, the defined requirements, and functional and logical architectures are implemented and dynamically linked together. Additionally, a multi-physical simulation model of the rover's power and mobility system is implemented. Requirements, architectures, and physical models are linked together to form a unique and comprehensive knowledge base, providing a vertical model-centric approach. The results of the simulation are used to conduct a trade study and deduct a design change for the system. The results presented in this study form the basis for a discussion aimed at evaluating the benefits and limitations of the MBSE approach mentioned in the scientific literature.

Keywords—*Model-based system engineering, System engineering, Planetary rover, Multi-physical simulation, Modelling, Simulink.*

I. INTRODUCTION

Space systems are becoming increasingly complex, and traditional document-based system engineering methods have shown their limits. Model-Based System Engineering (MBSE) is a recent approach to system engineering that uses models to represent the system's architecture, behaviour, and requirements. This approach has emerged as a promising methodology to overcome the limitations of traditional system engineering [1]. While MBSE has been recognized as a valuable approach in system engineering, its application to the field of planetary rover design, particularly in a reverse engineering context, is relatively unexplored [2].

This study investigates the challenges associated with system modelling using a reverse engineering approach on a novel application. This paper aims to showcase the benefits of the MBSE approach through a case study of a planetary rover design. The objective is to demonstrate how MBSE can address the challenges faced during the system modelling, analysis, and verification. The case study focuses on the utilization of the MathWorks MBSE toolchain, which offers a comprehensive set of modelling and simulation tools,

including Simulink and Simscape, for implementing the MBSE approach.

Traditional system engineering methods have been used to design planetary rovers, but these methods have limitations. Often document-based approaches are reliant on manual processes, and they can make the complexity difficult to manage efficiently [3]. This can slow the identification of system bottlenecks early in the design process and cause costly late design changes [4]. To measure the complexity of a system, factors such as the number of system pieces and source lines of code (SLOC) are often considered [1].

This paper presents a case study on the use of MBSE in the design of a planetary rover. The methodology section provides an overview of the adopted MBSE approach, detailing the modelling techniques and tools used in the case study. The results section presents the outcomes of the application of the MBSE approach to the planetary rover design, including the creation of system architectures, static and dynamic analyses, and simulation-based evaluations. The discussion section analyses the findings, highlights the strengths and limitations of the approach, and offers insights for further improvement. Finally, the conclusion summarizes the key findings and emphasizes the significance of the MBSE approach in addressing the complexity of space system engineering.

II. METHODOLOGY

A. Literature review

A review of the literature on MBSE and planetary rover design is conducted to identify the benefits and challenges of using MBSE in this domain. A survey of the tools, languages and methods used is conducted.

B. Definition of project requirements

a) Tools, language, and methodology used.

Using interoperable, documented, and familiar tools can drastically improve the adoption and effectiveness of an MBSE approach [5], with the objective to soften the learning curve, as it is often the most cited hurdle of MBSE. The MathWorks MBSE toolchain is chosen for all these reasons. It provides a comprehensive requirement management, system architecture and modelling tool in a single toolchain. The toolchain's methodology and language are also adopted.

b) Selecting a mission

NASA Mars Pathfinder mission is selected due to the manageable complexity of the mission. Additionally, the mission is composed of two interacting systems: the lander and the rover. These interactions could be modelled and studied. This idea was dropped later in the project due to time constraints. Finally, the mission ended more than 20 years ago, which enables the fetching of information more easily than new missions as more articles and papers can be accessible freely.

c) Refining the mission

An emphasis was put on studying the Sojourner rover as it was the main purpose of the thesis. It also constituted a manageable subject to architecture and model.

C. System Architecting

Using the previously defined mission requirements and framework the system architecture is derived. Different architectures of the rover are created based on official mission documents and published papers [6] [7] [8] [9]. The requirements and their implementation are defined and tracked in the different architectures using the Requirements toolbox. The functional, logical and physical architectures are created using the Simulink System Composer toolbox. Finally, architectures and models are unified into a single model using a traceability matrix.

D. System Analysis

a) Static analysis

Functions are defined to perform computations using the components of the architecture: objects and interfaces. System performances are derived based on the statistical analysis functions. Mass and power consumption budgets are obtained. The mass and power consumption of the power system and driveline are compared to the actual system properties for comparison. Variations of components are defined and organised into profiles to showcase different possibilities of the system design and their consequences on system properties.

b) Dynamic analysis

A simplified multi-physical model of the driveline and power system is modelled with the Simulink Simscape toolbox. The power consumption of the rover is modelled in different terrain environments. Finally, the model implementation is linked to the architecture and requirements model. Requirements are validated through the results of the model.

E. Trade study and design changes

The results of the static and dynamic analysis are used to base a trade study. The model is used to estimate the rover's autonomy in function of the terrain properties (slope, friction). It is derived and compared to the actual performance of the rover. The comparison highlights the limits of the model but showcases the possibilities of such a methodology.

A trade study balancing the rover's weight over its power consumption and autonomy is obtained from the model. As a result, illustrations of possible design changes are discussed.

F. Discussion

Finally, the implications, benefits, and drawbacks of the MBSE process are discussed. The MathWorks MBSE toolchain user experience is also discussed.

III. RESULTS

The project has yielded the following deliverables:

- A set of technical requirements derived from the publications and online documentation.
- A system architecture of the Sojourner rover with 3 different perspectives: Functional, Logical and Physical.
- A real-time, multi-physical simulation model of the Sojourner rover power and driveline system.
- From the physical model, an estimation of the power consumption of the wheel's engine under different terrain variations.
- A requirements traceability matrix tracing the implementation and verification of requirements in the different architectures and model implementations.

The system architecture model enabled a comprehensive representation of the Sojourner rover's components along with its interfaces, and their relationships. The use of a requirements traceability matrix allowed us to track the requirements of the Sojourner rover with their implementation in the model. The system's requirements were implemented in the different layers of the architecture. Finally, the dynamical analysis, conducted through real-time and multi-physical simulations provided valuable data for conducting a trade study and making design decisions.

It is important to note that the model used for analysis had limitations. The accuracy of the model depended on the assumptions made during the model design. However, given more time, these issues can be tackled.

As a result, a vertical implementation of the MBSE methodology is obtained, from requirements up to the physical modelling of the system. This work serves as a base for exploring the potential applications and discussing the use of MBSE for the conception of space systems.

Future work should focus on refining the physical model to explore the possibilities and limitations of modelling in the design process.

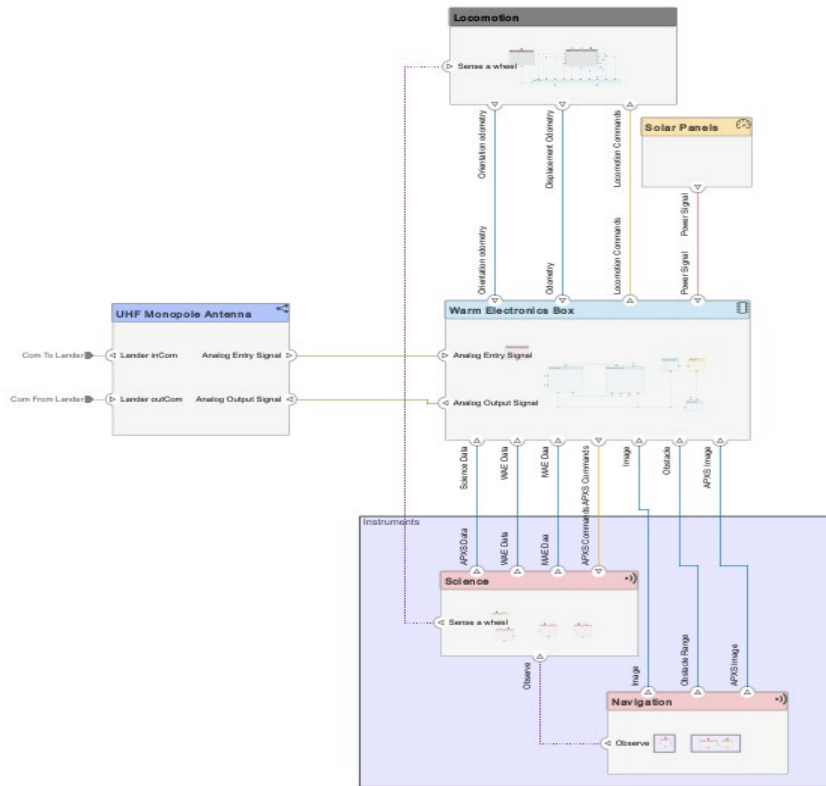


Fig. 1. Logical architecture, first layer.

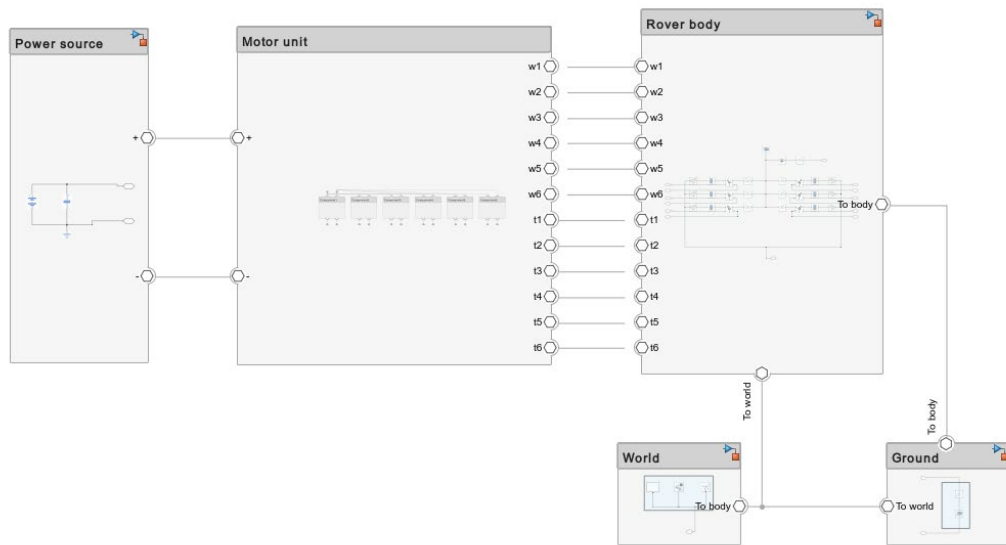


Fig. 2. Multi-physical simulation. Power source model (left) is connected to the motor unit (centre) in turn connected to the rover body driveline (right). The environment model is monitored via the two modules World and Ground (bottom right).

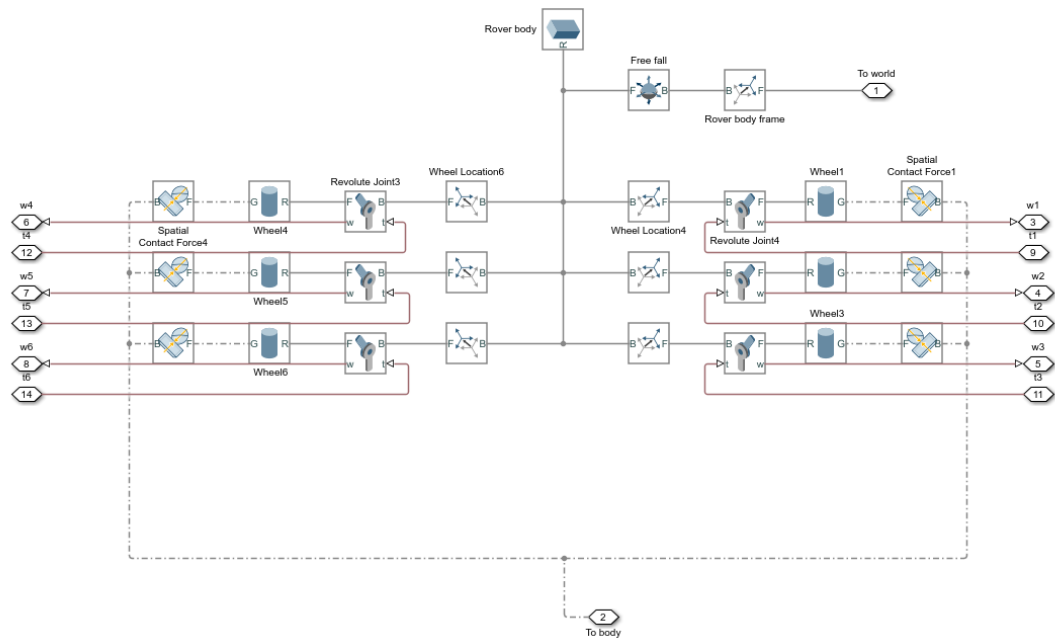


Fig. 3. Rover driveline model, connected to the world (bottom) and the wheels engine (right and left).

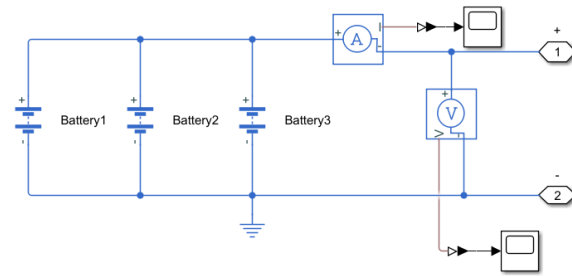


Fig. 4. The power source of the rover [10].

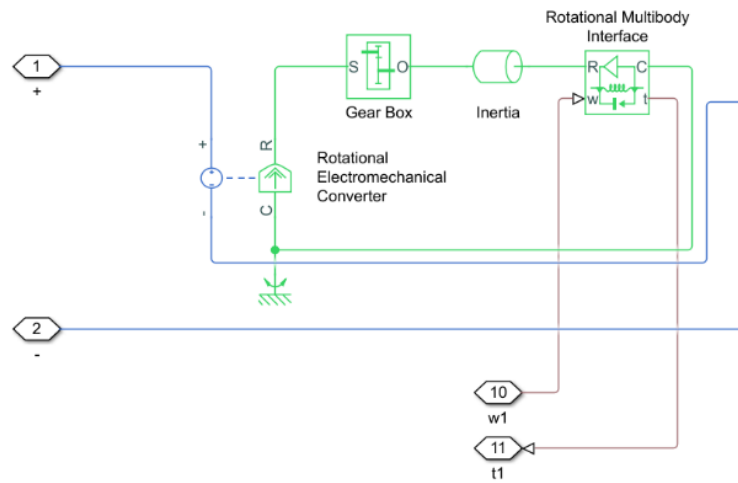


Fig. 5. Engine driveline subsystem model. Connections with the power source (left) and the environment (bottom right) are visible.

IV. DISCUSSION

The results obtained from the application of the Model-Based Systems Engineering (MBSE) approach to the planetary rover design case study have provided valuable insights into the benefits and limitations of this approach. Using MathWorks MBSE toolchain, and more specifically Simulink, it was possible to establish and analyse a rover system architecture and physical model.

The comparison between the Model-Based Systems Engineering approach and the classical systems engineering approach based on the results of this study highlights several key differences and advantages. The MBSE approach demonstrated its effectiveness in providing a systematic and structured framework for system analysis, design, and verification. Through the utilization of system architectures and traceability matrices, MBSE offered enhanced traceability and requirement management capabilities, ensuring that system components were appropriately allocated to meet the specified requirements. This facilitated a more streamlined and organized design process, allowing for early issue identification and improved decision-making.

In contrast, the classical systems engineering approach, which may not incorporate such advanced modelling and simulation techniques, could potentially encounter challenges in managing the increasing complexity of space systems. While both approaches strive to achieve system reliability and efficiency, the MBSE approach demonstrated a clear advantage in its ability to conduct real-time and multi-physical simulations, providing valuable insights into the system's behaviour and performance. The dynamic analysis using simulation models enabled informed trade studies, offering a more optimized and reliable system. For example, it was possible to showcase variations of architectures and their inherent properties (budget of mass, bill of materials) conjointly. A standard approach would have needed a document tracking the changes made in each version of the system and its properties. Another example can be a common task performed by the system engineers: the Interface Control Document (ICD). This task is automated by leveraging the MBSE framework while in a standard system engineering process, they are referenced manually in a spreadsheet.

Another of the key findings of this study is the emphasis on compatibility in the MBSE approach. The integration of various system components and models is crucial for accurate analysis and simulation. It was observed that the compatibility between the main model (architectures) used by system engineers and externally created models (physical simulation) significantly improved the usefulness of the central model. Future work should carefully plan and verify the compatibility of external software required for simulation before commencing the modelling process.

The limitations identified in the MBSE approach therefore include the potential lack of compatibility with the central model, which can limit the system analysis. Additionally, the reliance on simulation models for the verification of requirements poses challenges. It was evident that model limitations can be misleading, emphasizing the

need for caution and validation through empirical testing and real-world data.

The dynamic analysis, particularly the estimation of power consumption in the rover's mobility system, provided valuable insights for conducting a trade study and identifying design changes. However, it should be noted that the reliability of the power consumption model had limitations, which restricted the extent of conclusions that could be drawn from the results. However, the scope of this work was to showcase the possibility of vertical integration of MBSE and not to create accurate subsystems. Further work would be needed to improve the accuracy and reliability of the power model for more robust trade studies and design decision-making.

From an organisational perspective, it is important to acknowledge that the MBSE approach requires a significant upfront investment of time and effort in correctly setting up the system architectures. Additionally, the learning curve and transition from a document-based approach to a model-based one requires effort. Nevertheless, this initial investment leads to increased reliability and the ability to track changes throughout the product development stages. While it may take more time at the beginning, it is expected to reduce the time spent on fixing the system in later stages.

Furthermore, the successful application of the MBSE approach in this study aligns with the observations of previous researchers who have described it as a paradigm shift in systems engineering and enterprise organization. In this work, no text-based documentation is needed as the model is the documentation. This confirms the possibility of transitioning the paradigm of communication organisation in engineering.

In conclusion, the application of the MBSE approach to the design of a planetary rover has showcased its effectiveness in addressing the challenges associated with highly complex systems. The identified benefits, such as improved system analysis and design decision-making, align with the existing literature [4] [11]. However, certain risks, including compatibility issues and the need for cautious interpretation of simulation results, should be considered. Future work should focus on enhancing the accuracy, reliability, and capabilities of the model-based architectures and multi-physical simulations to further strengthen the application of the MBSE approach in space system design.

V. CONCLUSION

The objective of this study was to illustrate the benefits of the Model-Based Systems Engineering (MBSE) approach in the context of a planetary rover design case study. Through the utilization of the MathWorks MBSE toolchain, the MBSE approach was successfully applied and demonstrated its effectiveness in tackling the challenges of complex system engineering.

The findings of this work confirm that the MBSE approach offers significant advantages over traditional system engineering methods when dealing with highly complex systems such as planetary rovers. The use of system architectures, including requirements, functional, and logical

architectures, provided a structured and systematic framework for system analysis, design, and verification. The traceability matrix automated the requirement tracking and ensured the appropriate allocation of the system components.

The static analysis of the system using component properties and MATLAB functions allowed for an examination of the system's behaviour and performance. This analysis could enable early identification of potential issues and inconsistencies, contributing to improved system reliability and efficiency.

The dynamic analysis, conducted through real-time and multi-physical simulations, focused on estimating the power consumption of the rover's mobility system. This analysis provided insights into the energy requirements and helped in budgeting the rover's resources during its operational phase. Trade studies conducted using these results allowed for informed decision-making and iterative design improvements. Finally, using a traceability matrix it was possible to trace the implementation and verification of requirements in a centric model, hence showcasing the possibility of a fully vertical approach.

However, it is important to acknowledge the limitations of the power model used in the dynamic analysis. The reliability of power consumption estimations depends on the accuracy of the model and the assumptions made during its development. Further research is needed to refine and enhance the power model, ensuring more accurate and reliable results for design evaluations.

In conclusion, the application of the MBSE approach in the planetary rover design case study has demonstrated its effectiveness in addressing the increasing complexity of space systems. The creation of system architectures, coupled with static and dynamic analyses, facilitated a comprehensive understanding of the rover's behaviour, performance, and energy requirements.

The results of this project highlight the benefits of adopting the MBSE approach, including improved system analysis, traceability, and design decision-making. However, further research is needed to refine the power model and validate the simulation results through empirical testing.

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