Development of a space exploration rover digital twin for damage detection

Lucio Pinello[1], Marco Giglio[1], Claudio Sbarufatti[1], Francesco Cadini[1], and Giuseppe Francesco De Luca[2]

[1] *Department of Mechanical Engineering - Politecnico di Milano, Milano, 20156, Italy*
lucio.pinello@polimi.it, marco.giglio@polimi.it, claudio.sbarufatti@polimi.it, francesco.cadini@polimi.it
[2] *Agenzia Spaziale Italiana, Coordinamento Programmi di Ricerca e Relazioni col MIUR - Dir. Scienza e Ricerca, Roma, 00133, Italy*
giuseppefrancesco.deluca@asi.it

ABSTRACT

This study focuses on the creation of a digital twin of a space exploration rover to perform damage detection. The digital twin incorporates various subsystems of real rovers to accurately simulate the rover's behaviour. Damage detection is performed by introducing damages into the digital twin and comparing signals obtained in healthy and damaged conditions. By using the multiphysics model created by integrating different subsystems, the effect of damages can be observed in other subsystems of the rover. The study aims to demonstrate the potentiality of a digital twin for damage detection, reducing the risk of mission failure and data loss.

1. INTRODUCTION

In recent years, space exploration efforts have increasingly focused on the surface exploration of planets and satellites such as Mars and the Moon. This has been made possible through the use of rovers, which are capable of travelling across celestial bodies and conducting research activities. However, completing missions can be challenging, and problems must be addressed promptly to avoid the loss of scientific data or even the rover itself. Given the limited communication capabilities with Mars (Olson, Matthies, Wright, Li, & Di,), for instance, anomalies must be detected quickly, as there is no possibility of on-site human intervention. To face this problem, NASA started developing physical twins of its rovers, such as MAGGIE and OPTIMISM for Curiosity and Perseverance, respectively (Cook, C., Johnson, & Hautaluoma,) (Castelluccio,). At the same time, NASA and Siemens worked on a digital twin of Curiosity to analyse and solve heat dissipation problems caused by the Multi-Mission Radioisotope Thermoelectric Generator (MMRTG) using Simcenter 3D (M.I.T.,). Similarly, the European Space Agency (ESA) developed both a digital and a physical twin, called Amalia, for the Rosalind Franklin rover of the ExoMars mission to face possible issues that will arise (ESA,). Thus, digital twins and physical replicas are extensively used for space exploration rovers, mainly to analyse and face problems and to test control commands before sending them to the real rover. In this framework, the project ”DIGital twin di sistemi di Esplorazione lunare” (DIGES), in collaboration between Politecnico di Milano and Agenzia Spaziale Italiana, proposes a feasibility study for the application of digital twins for future space exploration rovers. Therefore, this study aims to create a digital twin of a space exploration rover using the MATLAB®-Simulink® environment and to use it to perform damage detection by simulating damages within the model. This strategy helps the interpretability of future, and maybe black-box, damage detection algorithms since the latter will be based on multiphysics databases, generated ad-hoc by injecting damage models in the digital twin. The digital twin incorporates various subsystems of real rovers, such as the energy harvesting system (batteries and solar panels), the driveline, the robotic arm, and the heating and cooling system, with all their interdependencies modelled. By doing so, it is possible to simulate the rover's behaviour in a lunar environment accurately, even if the model can be easily adapted to different celestial bodies. Damage detection is performed by introducing damages into the digital twin and comparing the signals obtained in healthy conditions with those obtained in damaged conditions. By using the multiphysics model created by integrating the different subsystems, the effect of damages and anomalies can be observed in the other subsystems of the rover as well. In summary, this study aims to demonstrate the effectiveness of a digital twin for damage detection in space exploration rovers, which could significantly reduce the risk of mission failure and data loss.

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2. SPACE EXPLORATION ROVER DIGITAL TWIN

A digital twin can be defined as a virtual representation of a system that spans its lifecycle, is updated from real-time data, and uses simulation, machine learning and reasoning to help decision-making (Armstrong,). For this study, a real space exploration rover, e.g., Curiosity, has been taken as a reference and then it has been modified according to the characteristics of the lunar environment. The digital twin has been developed in the MATLAB®-Simulink® environment to exploit the advantages given by the block-based modelling approach to represent real system behaviour at a very detailed level and to build multiphysics models thanks to the Simscape® toolbox.

2.1. Digital twin architecture

The digital twin has been developed starting from a Mathworks base model of a Martian rover (Miller,). This model considered only the structural components of the NASA rover Curiosity (e.g., chassis, suspensions, wheels, and robotic arm), the driveline motors, and the control algorithm for both cruising and sampling, but it did not implement the robotic arm motors, the energy harvesting and storage system, the heat rejection system, and the communication system. Thus, the model has been first adapted to the lunar environment by modifying the parameters of motors and gearboxes, and the external parameters such as gravity. Then, the model has been expanded by introducing the aforementioned subsystems.

The datasheets of the real components have been used for building a digital twin that is as close as possible to real systems:

- The solar panels implemented are the 30% Triple Junction GaAs Solar Cell - Type: TJ Solar Cell 3G30C – Advanced, by AzureSpace® which are mounted on the ESA rover Rosalind Franklin (Ferrando et al.,) (AzureSpace®,).
- The batteries are the MP 176065 xtd of Rosalind Franklin rover and are made by Saft®, they are Li-ion rechargeable batteries developed for extreme working conditions (Saft®,).
- The motors modelled are the Maxon® DC M32 ones (maxon®,) used on both Perseverance and Rosalind Franklin (maxon®,). A total of 16 motors have been included in the architecture, of which 4 are used as steering motors, one for each of the front and rear wheels, 6 are used as driving motors, and the remaining ones enable the movement of the robotic arm.
- The gearboxes are the pericyclic gearboxes that have been developed by NASA for Perseverance's wheels and robotic arm to allow precision positioning, high output torque, lower speed and lower inertia, and thus, low gyroscopic loads and low bearing loads (Krantz & Cameron,).

Concerning the heat rejection system, which is the rover's subsystem devoted to keeping its components in the working temperature range, it consists of active and passive components. The active components are the electric heaters, which are placed close to components that remain in a limited temperature range, such as motors and batteries, and thus the heaters are turned on and off depending on the temperature of the latter. The electric heaters included in the model are four per motor (Kempenaar et al.,), for a total of 64 heaters, and 12 for the battery pack and the Warm Electronic Box (WEB), which is the inside of the chassis of the rover where all the electronics are placed to be kept at the right temperature.

Moving on to the passive components, they are required to avoid overheating the rover, with the only exception represented by the Radioisotope Heating Units (RHUs) which are located both in the rover's WEB and close to the batteries (NASA,) (Hatakenaka et al.,). They are a constant source of heat thanks to the decay of isotopes and, considering solar-powered rovers, RHUs are crucial because they allow heating without turning on electrical heaters, thus saving battery power, especially during night-time when the rover cannot rely on solar panels. Besides the RHUs, there are:

- An external S13GP6NL0-1 white painting to minimize radiation heat transfer (Bradford, Rabinovitch, & Abid,), that is the one used on Perseverance.
- An insulation layer made of a CO_2 gas cap, as for Curiosity, Perseverance, and Rosalind Franklin (Hatakenaka et al.,).
- Thermal switches, heat pipes, thermal straps, thermal interface materials, and phase change materials (Weston,) that are used to dissipate heat.

The aforementioned components are modelled in Simulink® according to the existing libraries of the Simscape® toolbox and by setting the blocks' parameters according to the available datasheets, in particular:

- The DC motors are represented by the Motor & Drive (System Level) blocks.
- The Simple Gear blocks model the pericyclic gearboxes.
- The solar panels are modelled with the Solar Cell blocks.
- The Behavioral Battery Model blocks represent the batteries.
- The RHUs are represented by constant Heat Flow Rate Source blocks producing 1.1 W each.
- The electric heaters are represented by Heat Flow Rate Source blocks which generate either 0W or 43W depending if the component temperature is respectively above or below 278.15K.
- The effect of the painting is modelled by adjusting the parameters of the Radiative Heat Transfer blocks.
- The Conductive Heat Transfer blocks simulate the CO_2 insulation layer.

- The passive components required for cooling are modelled according to the thermal conductance curve of the PGS thermal straps presented in (Weston,), in which the cooling power depends on the temperature of the components to which they are connected. Thus, they are modelled as Heat Flow Rate Source blocks generating negative thermal power to cool the components depending on their temperature.

An overview of the space exploration rover digital twin is shown in Figure 1, where the aforementioned subsystems are modelled and interconnected: the effect of temperature on motors and batteries is considered and all the subsystems are connected to the Power subsystem, e.g., the energy harvesting and storage system, to allow the correct functioning of motors and electric heaters. Noises are added numerically in Simulink® to account for uncertainties and noises of the real system.

2.2. Digital twin functionalities

The space exploration rover digital twin described can cruise and perform sampling operations. In this context, a communication system has been implemented to send messages after mission tasks such as the start of the mission, the end of the cruising, the successfulness of the sampling operation, and the storage of the sample. The digital twin can also be used for non-operative purposes, such as during the night when a rover that relies on solar panels limits the capabilities to save batteries' life. In this scenario, the digital twin can be used to evaluate the evolution of the temperatures of the several components of the rover, also checking the correct functioning of the electric heaters. Thus, using the digital twin for prognostics and health monitoring seems obvious. To perform health monitoring, damages have been implemented in the model thanks to the flexibility of Simulink® blocks, as will be seen in the next section.

3. DAMAGE IMPLEMENTATION

Since the digital twin must cover the life of the rover, it must be able to replicate the rover's behaviour in both healthy and anomalous conditions since damages can occur during the mission, as already happened for the NASA Martian rovers. For example, Opportunity's right-front wheel actuator jammed due to a gearbox jam and the wheel was stuck and rotated at 7°, while the azimuth actuator of Opportunity's robotic arm resulted in fault due to a motor winding break (Callas,). Another example is given by the Pathfinder mission (e.g., the Sojourner rover) for which NASA has estimated a degradation rate of 0.28% per sol only due to dust deposition on solar arrays (Landis, Kerslake, Jenkins, & Scheiman,), this problem is also known as soiling. Soiling can also cause erosion of the anti-reflection coatings that are used to avoid the 4% optical loss of incident light due to reflection (Aghaei et al.,). Thus, in this section, some simulations in a damaged rover scenario are presented in diurnal operating conditions, under the assumption that missions are conducted when there is energy production by the solar panels to preserve battery life. It is worth stating that implementing damages in the digital twin helps both develop damage detection algorithms and enhance their interpretability.

3.1. Driving motors anomalies

In this section, the analysis is going to focus on motor failures that happen during the mission, in particular, the failure implemented is a short circuit and it is set to happen after 60s from the beginning of a mission in which the rover cruises along a path which comprehends both straight and curved sections. The short circuit is an anomalous condition that can be due to sudden voltage shocks, long-term exposure at high temperatures, and insulation drop. When a motor breaks or is damaged and cannot work, it gets stuck. This means that the corresponding wheel cannot drive or steer anymore or that the robotic arm loses some degrees of freedom. Generally, the rover can continue to operate with a wheel stuck but it depends on the stall position of the wheel if the damaged motor is a steering one since a failure of one or more steering actuators with the wheels far from straight would compromise not just steering, but straight driving as well (Callas,). Looking at Figure 2, it is possible to see that the middle motors on both sides and the rear motor on the right side supply the extra torque required for driving due to the lack of torque from the left-rear motor. This behaviour is reflected by an increase in the absorbed current by the aforementioned motors, with the greatest contribution given by the left-middle driving motor, which is on the same side as the faulted motor. The main difference between the steering motors' absorbed current is due to the increase in mission duration of 7s. However, a significant deviation in the absorbed current of the left-rear steering motor is shown in Figure 3, which is the same wheel of the faulted driving motor.

3.2. Solar panels anomalies

This section is going to focus on the anomalies of solar panels. In particular, the focus is set on the regolith coverage of the solar arrays, on the possible thermal cracking caused by the extreme temperature difference between lunar day and lunar night, and on general malfunctions. The anomalous conditions are modelled with a solar panel efficiency loss. Two efficiency reductions have been considered: a mild loss of 30% of efficiency and a severe loss of 50%. The power generated by each solar panel is shown in Figure 4 for both healthy and damaged conditions. In particular, the first central fixed panel shows the greatest power reduction, which is the one with the larger exposed surface.

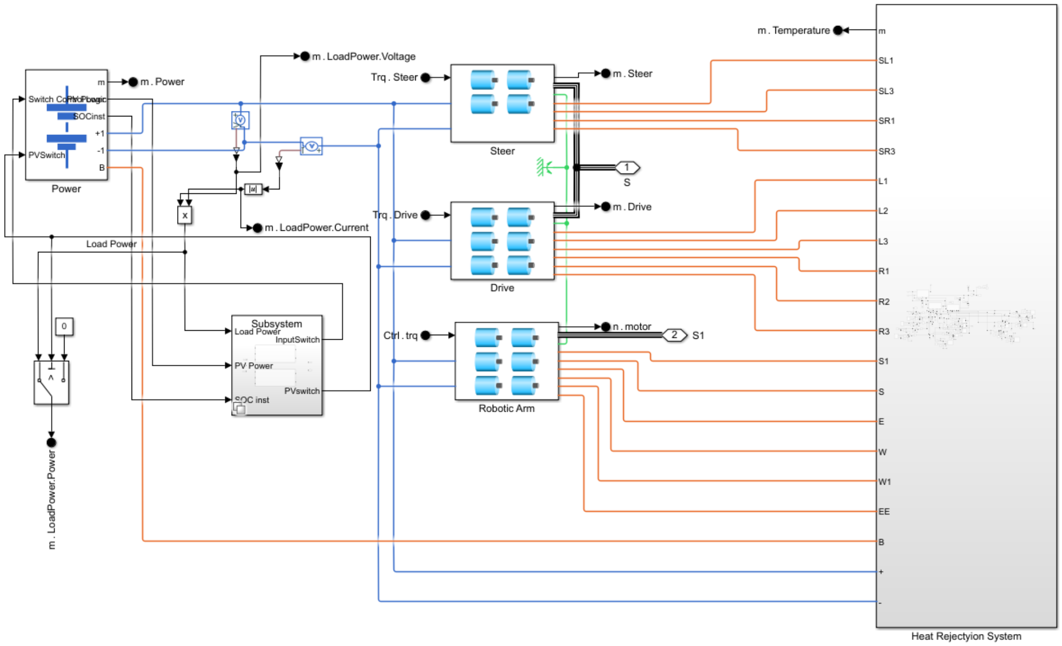

Figure 1. Overview of the functional subsystem of the space exploration rover digital twin

3.3. Electric heaters anomalies

This section is going to focus on the anomalies of electrical heaters. The simulated conditions are one of the heaters stuck on during the lunar day (worst case for heat dissipation). Since the motors' behaviour is not affected by the malfunction of a specific electrical heater, and the same is true for the temperature of components far from the faulted electrical heater, the focus is set only on the temperature difference between the healthy and the damaged condition for each specific component. The results are shown for the robotic arm motors in Figure 5 and it is possible to see that the motors' temperature rise is extremely fast since it exceeds the allowed working temperature range in a small period.

4. DISCUSSION

This framework proves that it is possible to detect anomalies by exploiting a digital twin capable of real-time operations for damage detection purposes and that the latter can be used to create a database and train machine learning algorithms, such as support vector machines, to detect damages in real time.

The simulation results show that an anomaly in one motor affects the other motors, even those devoted to steering instead of driving. It is worth noticing that the digital twin seems to be very sensitive concerning failures of the rear motors and that one can distinguish an anomaly of the current sensor from motors' anomalies by looking at the current absorbed by all the motors. Moving on to the solar panels, the rover proved to be robust with respect to anomalies such as lunar regolith deposition thanks to a redundant design, since the rover is still able to complete the mission even with a severe efficiency loss. Eventually, malfunctions in electric heaters cause a fast rise in motors temperatures, causing the motor to be out of use.

5. CONCLUSION

This work focused on the usage of digital twins for damage detection purposes in space exploration rover applications, which are high costs and high risks systems due to their operative condition. The results presented address the anomalous conditions of driving motors, solar panels, and electric heaters, but the digital twin described can be used for implementing several damages to the various subsystems. Future applications may be regarding the creation of a database for machine learning algorithms to perform damage detection or implementing model updating algorithms to enable real-time autonomous damage detection. In general, this study proposes a fertile framework for developing digital twins to help understand the behaviour of real systems, with the help of existing physical twins. Being a preliminary feasibility study, no validation and verification are foreseen in this stage. However, if the project will continue there will be space for the validation of the digital twin performances, allowing also to enhance the observation of anomalies effects.

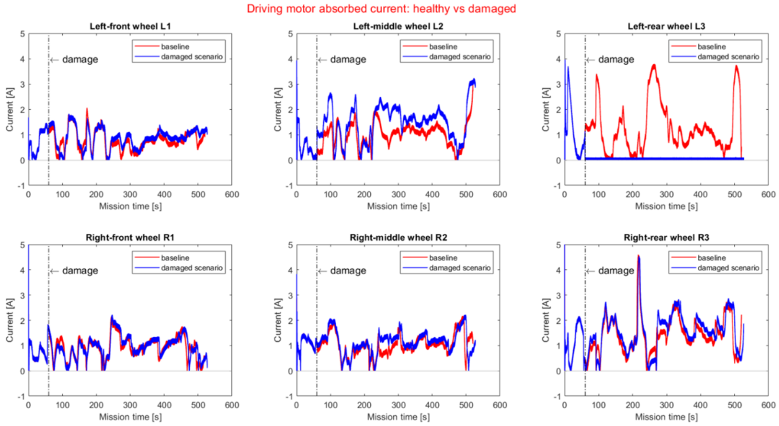

Figure 2. Driving motors absorbed current when the left-rear wheel driving motor is faulted.

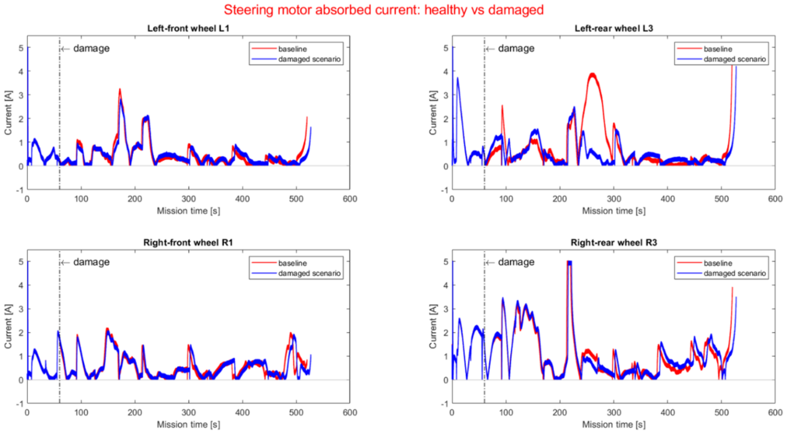

Figure 3. Steering motors absorbed current when the left-rear wheel driving motor is faulted.

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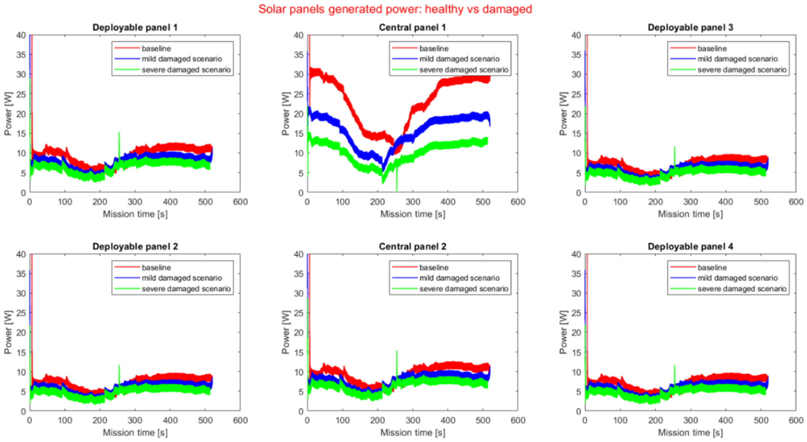

Figure 4. Solar panels output power under healthy, mild damaged and severe damaged conditions.

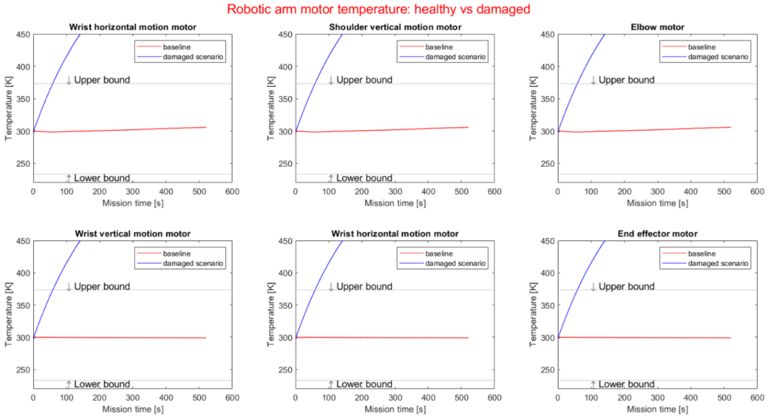

Figure 5. Robotic arm motors' temperature in the daytime when the electrical heaters are stuck on.

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