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SAMPLE FETCH ROVER: ENABLING TECHNOLOGIES FOR PLANETARY MOBILITY

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Abstract

The Sample Fetch Rover (SFR) is a novel surface vehicle studied for Mars Sample Return (MSR). The rover is designed as a multi-mission transportation system with no scientific payloads on board and the only objective of acquiring sample tubes previously deposited on the surface and delivering them to a lander in a strict timeframe. Its mission imposes demanding requirements, such as traverse distance, timeline, mass, volume and energy, which necessitate the development of new technologies or the augmentation of existing ones. Following the decision not to implement SFR in the MSR Campaign, these technologies are becoming attractive for future rover missions to Mars and to the Moon. This paper summarizes the development of these technologies and their applicability to future use cases. The SFR mission profile and design drivers are described herein, along with the system architecture established in response to them. What follows is an overview of the key technologies studied for SFR, focusing on the most critical or innovative ones, such as locomotion, navigation and sample tube acquisition. The summary includes the other significant aspects of the design: structure, thermal control, mechanisms, control electronics, power, avionics and communications. For each of these, the main technological advancements and their relevance to forthcoming rover missions are discussed.

Key words

Sample Fetch Rover; Mars Sample Return; Planetary Mobility;
Space Robotics; Technology Development; Planetary Exploration.

Abbreviations

AutoNav: Autonomous Navigation
AVS: Added Value Solutions
BOL: Beginning Of Life
CFRP: Carbon-Fiber-Reinforced Polymer
DELIAN: DExtrous LIghtweight Arm for exploratioN
DEM: Digital Elevation Model
DOF: Degree Of Freedom
EOL: End Of Life
ERO: Earth Return Orbiter
ESA: European Space Agency
GNC: Guidance, Navigation and Control
GRC: Glenn Research Center
HDRM: Hold-Down and Release Mechanism
HEPA: High-Efficiency Particulate Air
IABS: Integrated Avionics Box Subsystem
IMU: Inertial Measurement Unit
LCL: Latching Current Limiter
LocCam: Localization Camera
MDA: MacDonald, Dettwiler and Associates
MSR: Mars Sample Return
NASA: National Aeronautics and Space Administration
NavCam: Navigation Camera
NavStop: Navigation Stop
NEA: Non-Explosive Actuator
OBC: On-Board Computer
PCDE: Power Conversion and Distribution Electronics
PCMC: Phase Change Material Capacitors
PDR: Preliminary Design Review
RAS: RSTA Acquisition System
RDC: RSTA Detection Camera
RHU: Radioisotope Heater Unit
RSTA: Returnable Sample Tube Assembly
SDRAM: Synchronous Dynamic Random-Access Memory
SFR: Sample Fetch Rover
SOET: Surface Operations Engineering Tool
VBDS: Vision-Based Detection Software

1. Introduction

The Sample Fetch Rover (SFR) was studied by Airbus Defence and Space Ltd. in Stevenage, UK, for the European Space Agency (ESA) in the context of the Mars Sample Return (MSR) Campaign [1]. MSR is a collaboration between the National Aeronautics and Space Administration (NASA) and ESA, with the objective to return samples from the surface of Mars for scientific study on Earth. The campaign is based on three missions:

1. A caching mission, which collects and seals samples inside tubes for future recovery. This mission is currently being carried out by NASA's Perseverance rover in Jezero Crater.
2. A retrieval mission, which acquires the sample tubes and launches them into Mars orbit. This mission is expected to launch in the late 2020s.
3. A return mission, which captures the tubes in Mars orbit and delivers them to Earth. This mission is expected to launch in the late 2020s and return to Earth in the early 2030s.

In the international MSR conceptual architecture established in 2018, the retrieval mission envisaged a lander from which a rover would have been deployed to acquire the sample tubes deposited on the surface. That rover was SFR, one of the European contributions to MSR. In 2022, this part of the campaign underwent a significant revision, leading to the removal of SFR and the termination of its development. This was done to reduce complexity and cost, but was also driven by a shift of priority to the ExoMars mission. Alternative studies were carried out to replace SFR with a much smaller rover equipped with simpler technologies [2]; however, the work discussed herein focuses on the original SFR design as it was intended in the 2018 MSR architecture.

At the time of its cancellation, SFR had just passed its Preliminary Design Review (PDR) successfully, which means that the design was mature enough for implementation, and significant progress had been made in developing its critical technologies. This article provides an overview of these technologies and the knowledge gained during the development of SFR. This research builds upon previous experimentation with Mars rover testbeds performed by ESA in view of a forthcoming fetching rover [3]. Here, we present the flight design of that rover, the process that led to it, and its relevance to future exploration missions.

The development of SFR benefitted significantly from technology already available from the ExoMars Rosalind Franklin Rover. Unlike Rosalind Franklin, SFR does not carry any scientific instruments, as the goal of MSR is to perform scientific observations on Earth. Its sole objective is to locate and retrieve up to 30 sample tubes, delivering them to the lander in time for launch. As such, the rover is designed to be a highly capable transportation system, with emphasis on fast and long traverse, autonomy, robotic manipulation, compactness and energy efficiency. This can be achieved in part by adapting ExoMars technologies to SFR, but some aspects inevitably require new developments. The relevance and use of ExoMars technology are mentioned in these pages where applicable.

This paper presents the novel solutions and the advancements in existing technology achieved in the development of SFR. Sections 2 and 3 introduce the SFR mission and the rover's architecture, while the following ones offer a more detailed description, subsystem by subsystem: Locomotion (Section 4), Guidance Navigation and Control (Section 5), Sample Tube Acquisition (Section 6), Structure and Thermal Control (Section 7), Mechanisms and Control Electronics (Section 8), Power, Avionics and Telecommunications (Section 9).

Particular emphasis is given to the areas that respond to the characteristic challenges of the SFR mission, such as locomotion and robotics, which are also those characterized by the most notable innovations. Although SFR will not be launched, these technologies are attractive for future planetary exploration missions to Mars and to the Moon. Especially on the latter, growing interest towards missions that are not only scientific, but more utility-driven in nature, makes these capabilities especially relevant.

2. State of the Art

A total of six rovers have been successfully operated on Mars to date:

- Sojourner (NASA, solar-powered microrover) [4]
- Spirit and Opportunity (NASA, solar-powered twin rovers of medium size) [5]
- Curiosity (NASA, nuclear-powered large rover) [6]
- Zhurong (Chinese Space Agency, solar-powered, similar in size to Spirit and Opportunity) [7]
- Perseverance (NASA, same platform as Curiosity, accompanied by the rotorcraft Ingenuity) [8]

They are all wheeled vehicles (all with 6 wheels), ranging in size from 11.5 kg of Sojourner to 1025 kg of Perseverance. Many of them are solar-powered, while Curiosity and Perseverance use a Radioisotope Thermoelectric Generator (RTG) as their power source. Even the solar-powered rovers above use radioactive material to provide night-time heating.

SFR relies significantly on the knowledge acquired in the operation of NASA rovers, but the technology in its design is, in fact, much closer to the European Rosalind Franklin Rover, built and qualified for the ExoMars Mission in 2019, but not flown yet. Rosalind Franklin can be considered a medium-sized, solar-powered rover, with a total mass of 310 kg. Like the other rovers listed above (except for Sojourner, which is an experimental vehicle), Rosalind Franklin is built like a “science laboratory on wheels”. The vehicle is designed to maximize the scientific payload on board and accommodate numerous instruments to study the surface of Mars. This means that resources to other subsystems, in particular mass and volume, were significantly constrained.

ExoMars represents the culmination of decades of European development and testing of planetary rovers. Its sophisticated instruments include a drill, a chemical analysis laboratory, a ground-penetrating radar and high-resolution cameras. Its compact locomotion system drives at a modest speed (1 cm/s) but can negotiate rugged terrain. On-board autonomy allows the rover to cover distances up to 70 m in a sol (a Martian day, equivalent to 24.6 hours) with minimal intervention from mission controllers. During the night, the rover is kept warm by Radioisotope Heater Units (RHU) inside the insulated volume of its central body. An allocation of heat and electrical power is dedicated to the large scientific payload, which totals nearly 47 kg, distributed around the rover. On SFR, no such payload is present. As described in the following chapters, this allows a departure from ExoMars heritage in a few areas and some noteworthy increases in performance and functionality.

In response to new design drivers (see Section 4), it became necessary to improve several ExoMars technologies for the SFR mission. In particular, SFR is able to traverse further and much faster than ExoMars, thanks to a more capable locomotion subsystem, with higher power, higher efficiency actuators and an enhanced wheel design. The new 4-wheel architecture was also mechanized to achieve a better packaging ratio. SFR implements a higher degree of autonomy, especially for navigation and robotic operations. The functions used to recognize, acquire and manipulate payloads are entirely new, as ExoMars is not equipped with a robotic arm. Furthermore, the use of radioactive material was forbidden on SFR, so its thermal control relies on new strategies, such as thermal capacitors and electronics with an very low-power sleep mode.

3. SFR Mission Profile

The mission objective of SFR is to retrieve up to 30 Returnable Sample Tube Assemblies (RSTAs, or, more commonly, sample tubes) and deliver them to the lander, from where they will be launched into orbit. The tubes would have been previously deposited by Perseverance at a "depot" site, which could be up to 2 km from the lander’s touchdown location. To achieve its objective, the SFR mission goes through the following main phases:

1. Egress from the lander
2. Deployment and commissioning
3. Outbound traverse to the depot
4. Acquisition of sample tubes
5. Return traverse to the lander
6. Transfer of tubes to the lander

As the landing site and the depot location were still unknown during the SFR development, the rover had to be designed as a multi-mission machine, with sufficient flexibility to meet the required timeline for various combinations of landing sites and candidate depots. This produced an intricate network of possible paths that the rover could follow on the surface.

Such a variety of scenarios required the development of new tools to analyze a large number of missions in a statistical manner. The Surface Operations Engineering Tool (SOET) was developed by Airbus in response to this need. SOET provided the capability to simulate each one of the possible paths under varying conditions, for a total of several thousands of cases. The variable parameters included the Martian weather (temperature profile, airborne dust and solar flux, according to environmental models informed by previous missions) as well as the timeline (dates of the landing and launch from Mars, time spent at the sample depot). While a detailed description of SOET is out of the scope of this paper, its outputs can be summarized as the number of cases in which SFR successfully completes its mission, the primary cause of failure for the unsuccessful ones (e.g., insufficient time, insufficient energy…) and various statistics on demand. This approach proved extremely useful for an acquisition and delivery mission like that of SFR. More generally, this type of tool is applicable to any surface mission in an unknown or unstructured environment, including different planetary bodies, as long as the environment modelling is updated accordingly.

4. System Architecture

The SFR design is shaped in response to its unique mission requirements. The most influential design drivers are the following:

- Operational timeline. The limited time available pushes towards fast traverse and high autonomy to minimize reliance on ground control.

- Lander interface. It defines the total mass allocation, the stowed volume and the deployment strategy.
- Limited energy, as a purely solar-powered system. Requires efficient locomotion to maximize the daily range and a low-power sleep mode to survive the night on battery energy.
- Retrieval of hardware from an unstructured environment. Necessitates capable robotic and vision systems to identify and handle the sample tubes.
- Planetary protection. Strict contamination control is required to protect the Martian environment. This influences the materials choice, integration and cleaning procedures.

While the above drivers are specific to the SFR mission, it should not be forgotten that other design drivers are implicit in the fact that the rover has to operate in the remote and hostile environment of the Martian surface. The SFR technology must respond to challenges such as the large diurnal and seasonal temperature variation (from -125°C to 20°C), the presence of dust in the atmosphere (affecting the amount of sunlight available) and in contact with the hardware (causing contamination, abrasion and occlusion), the rugged terrain and the limited availability of communication with ground control, due to the distance (from 3 to 22 minutes one-way light time) and the intermittent access to relay satellites around Mars.

The development of the rover, guided by all these design drivers, converged onto the physical architecture reported in Figure 1, which shows the vehicle in its stowed (on the lander) and deployed (on the surface) configurations. It should be noted that both illustrations show the rover in its upright orientation, but it is actually stowed on the lander upside-down.

The external layout of SFR is rather typical for solar-powered Mars rovers, with a central body that forms a thermally-controlled enclosure for sensitive components, a deployable solar array and a camera mast on the top deck. Less common is the locomotion architecture, using four large compliant wheels. At the front of the rover are located the robotic arm and the equipment necessary to handle and store the sample tubes. The thermally-controlled volume of the rover body accommodates the avionics, the battery, Inertial Measurement Units (IMU), transceivers, heat storage units and loop heat pipes for thermal control. Table 1 reports the mass budget associated with this architecture.

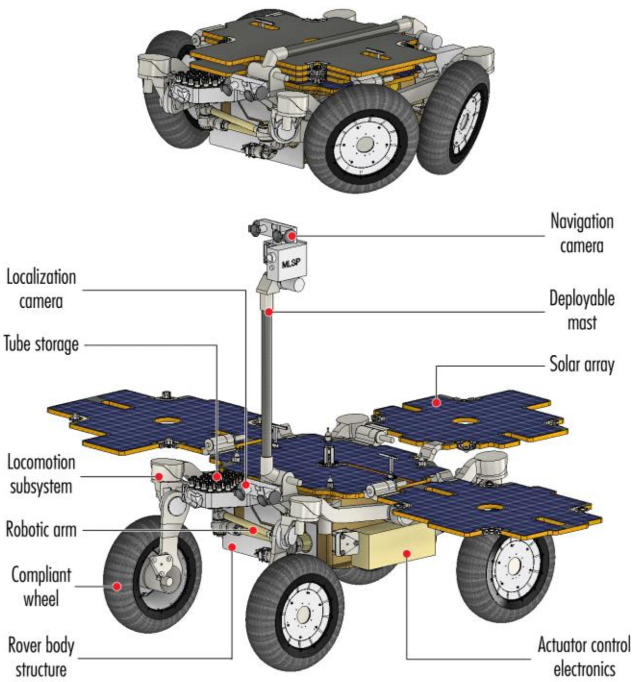

Figure 1 – SFR stowed and deployed with main external components

Item	**Mass (kg)**	**Margin**	**Total (kg)**
Body structure	21.9	15%	25.1
Thermal control	10.8	16%	12.5
Solar arrays	22.5	13%	25.4
Locomotion	60.2	21%	72.8
Arm and gripper	9.4	16%	10.9
Tube storage	1.8	15%	2.1
Mast	6.1	20%	7.3
Cameras	5.0	15%	5.7
Actuator control electronics	17.1	20%	20.6
Avionics	13.4	8%	14.4
IMUs	2.0	5%	2.1
Telecoms	2.7	8%	2.9
Battery	10.8	4%	11.2
Harness	4.5	30%	5.9
Lander interface hardware	11.0	20%	13.2

Sub-total (kg)	232.0
System margin	15%
Total with system margin (kg)	**265.6**

Table 1 – SFR mass budget

One further consideration contributing to the SFR architecture's definition is the strong push to use readily available technologies wherever possible. MSR required SFR to follow Perseverance within a few years from the collection of the tubes, leading to a rather compressed schedule for the rover’s development. Being SFR designed by the same Airbus team that built the ExoMars Rover, the possibility to use already proven technology became highly desirable to reduce risk. The outcome was a fusion of heritage ExoMars technology and innovative solutions, as detailed in the following pages. Table 2 compares some key features of the two vehicles.

Feature	**ExoMars**	**SFR**
Mass	310 kg	266 kg
Power	140 W at noon	120 W at noon
Locomotion architecture	6 wheels, triple bogie	4 wheels, rocker arm
Ground contact footprint (L x W)	1.3 x 1.4 m	1.3 x 1.1 m
Cruise speed	1.1 cm/s	6.7 cm/s
Target distance	4 km	5 km
Mission duration	218 sols	345 sols
Survival heating	3 x 8.5 W RHUs	Electric heaters

Table 2 – Comparison between ExoMars and SFR designs

From these high-level features, it can already be observed that the two vehicles are broadly similar, with a few exceptions: SFR uses a four-wheel architecture (primarily driven by the accommodation on the lander), it is significantly faster (to meet the timeline requirements, as described in Section 4) and uses battery-powered heaters for night survival (with nuclear material not being allowed onboard, as discussed further in Section 7).

5. Locomotion

The SFR locomotion uses a four-wheeled rocker arm suspension, designed by MacDonald, Dettwiler and Associates Ltd. (MDA) in Toronto, Canada. Its architecture and the main components are shown in Figure 2.

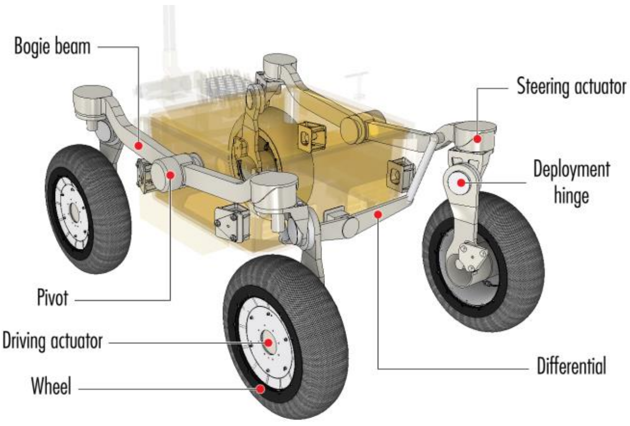

Figure 2 – SFR suspension with key components, seen from the rear of the vehicle

This is a passive, non-sprung suspension mechanism, composed by two lateral beams, named bogies, oscillating around pivot joints. Onto each bogie are mounted two wheels with their actuators. The bogies are connected by a differential linkage that confers a pitch-averaging behavior to the system, i.e., the pitch angle of the rover body is maintained at an angle that is the average between the pitch angles of the two bogies, even when traversing large obstacles.

The mechanization that allows such pitch-averaging behavior is obtained by mounting each bogie beam to the side of the rover body frame through freely rotating pivot joints. Oscillation of the bogies around the pivot joints allows the wheels to achieve contact with the ground on uneven terrain. However, if no further constraints were added, the rover body would be free to pitch uncontrollably. To remove an additional degree of freedom, and achieve the pitch-averaging behavior, a differential arm is mounted to the rear of the vehicle through another freely rotating pivot. The differential arm is connected to each bogie by tie rods with spherical bearings. Such linkage constrains the rotation of the bogies with respect to the rover body to be equal in magnitude and opposite in direction. In other words, the pitch angle of the rover body with respect to the ground is the average of the pitch angles of the two bogies.

Figure 3 provides an example of this principle: an obstacle causes the displacement of a wheel and the corresponding bogie rotates with respect to the ground by an angle β, while the other remains horizontal. The rear differential constrains the bogie rotations to be equal and opposite with respect to the rover body, or respectively +β/2 and –β/2. The result is that, with respect to the ground, when one bogie is pitching by an angle β and the other is flat, the rover body is pitching only by an angle β/2, achieving the aforementioned pitch-averaging function.

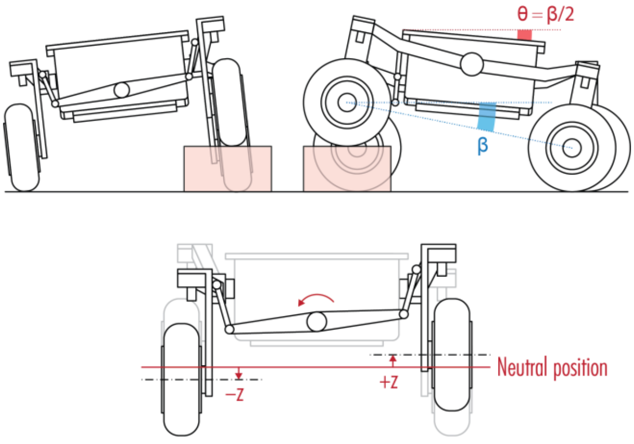

Figure 3 – Pitch-averaging behavior when surmounting an obstacle (top) and differential kinematics (bottom)

This arrangement makes the vehicle statically determined on four wheels on uneven terrain. The pitch-averaging behavior, typical of the rocker arm suspension, is particularly desirable on planetary rovers as it maintains solar panels and onboard sensors close to their optimal orientation.

Meeting the stringent timeline requirements and rapidly traversing rugged terrain necessitates a large and capable locomotion subsystem. However, the rover’s locomotion architecture is closely coupled to that of the lander: in terms of volume, as a more compact and simpler lander limits the space for the locomotion hardware, but also in terms of performance, as a more accurate and capable lander delivers the rover to optimal locations and requires less traverse distance. The allocation of mass and volume between rover and lander was subject to extensive trade-off in the early phases of the study, which converged on the configuration described herein. As shown in Figure 1, the locomotion hardware folds around the rover body to achieve a compact package, shaped to match the natural conical profile of the aeroshell. The stowed volume is, in fact, one of the key drivers behind the choice of a four-wheel layout, which better adapts to the lander.

A four-wheel architecture usually has some performance limitations compared to a six-wheel one, especially in its ability to climb obstacles. In light of this, maximising the performance of the wheels becomes particularly important. Such reasoning contributed to the selection of the superelastic Mars Spring Tyres developed by NASA’s Glenn Research Center (GRC) in Cleveland, OH, USA [9].

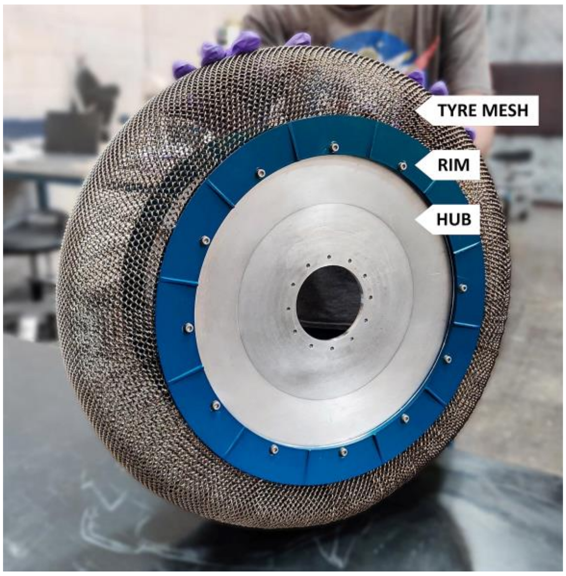

Figure 4 – SFR wheel and tire assembly

The spring tires are an evolution of the wire mesh tires of the Apollo Lunar Roving Vehicle. As shown in Figure 4, they are constructed by a series of inter-coiled helical springs that form a toroidal mesh, clamped at the wheel rim. The mesh deforms under load to contour to the terrain surface, producing excellent traction and obstacle-enveloping properties. The springs are made of a special nickel-titanium shape-memory alloy that exhibits superelasticity at Mars surface temperatures, allowing greater compliance without plastically deforming the spring elements. The fully metallic construction ensures compatibility with the harsh thermal and radiation environments on Mars. The outer diameter of the SFR tire is 550 mm.

To achieve the required maneuverability, especially demanding in the proximity of sample tubes, each SFR wheel is controlled independently by steering and driving actuators. This allows the rover to follow any curved trajectory, turn on the spot and move linearly in any direction with respect to the rover body, also called “crabbing”. The two types of actuators share a similar architecture and use some fairly consolidated technologies, already applied to the ExoMars Rover [10]. However, these technologies were applied to an overall new design, in response to different mission needs. In particular, the timeline and energy limitations require the SFR actuators to provide higher angular speed and higher efficiency than the ExoMars ones. A comparison of some key specifications of these actuators is provided in Table 3. In this table, efficiency represents the ratio between the mechanical power at the wheel and the electrical power at the actuator’s input. This is especially critical at cold temperatures, where the geartrain lubricant is at the limit of its working range.

Feature	**ExoMars**	**SFR**
Max. torque	87 Nm	88 Nm
Max. output speed	1.27 rpm	4.12 rpm
Unpowered holding torque	35 Nm	28 Nm
Efficiency at -60°C	30%	55%
Actuator mass	1.89 kg	2.70 kg

Table 3 –ExoMars and SFR drive actuator specifications

The actuators’ architecture is based on a Maxon DCX 32L brushed DC motor, chosen for its proven reliability, good power density and simple control electronics. This drives a four-stage planetary gearbox with a 1738:1 gear ratio, supported by a titanium housing and a main cross-roller bearing. Sensing is performed by a magneto-resistive encoder on the motor and a custom potentiometer on the output (for steering actuators only), while thermal control uses electric heaters and resistive temperature sensors. The assembly is sealed by a Teflon rotary seal to prevent ingress of soil particles. One new element, never implemented before on European rovers, is an active friction brake, embedded in the actuator, which can rapidly stop the vehicle in an emergency and keep it stationary without power.

The choice of a planetary-only geartrain (as opposed to planetary and Harmonic Drives in series, used on ExoMars) proved decisive in achieving the required speed and efficiency. So did the optimized thermal design, with warm-up heat applied to the first gear stages and a strong heat rejection path from the motor to the environment. The outcome at vehicle level is that, on a benchmark cruise terrain, the SFR locomotion is expected to need only 1.2 kJ/m to advance, while the ExoMars Rover's locomotion would require 6.9 kJ/m under the same conditions. In addition to the actuators' efficiency, other factors that contributed to this significant improvement are the lower number of wheels (leading to lower energy dissipation in joints and ground interaction) and the upgraded wheel design (higher energy restitution under load).

The novel aspects of the SFR locomotion (four-wheel suspension, superelastic tires, actuator design) necessitated early testing to increase their maturity and reduce risk on the compressed development schedule. Wheel prototypes of increasing fidelity were built and characterized, while breadboard actuator models were tested for performance and durability. Ultimately, a full-scale model of the vehicle was built, with a reduced mass to be representative – on Earth – of its weight on Mars (38% of Earth's gravity). This prototype was tested at Beyond Gravity AG, Switzerland, on Martian simulant terrains on a specially-built tilting test bed to gain confidence in the performance of the whole system.

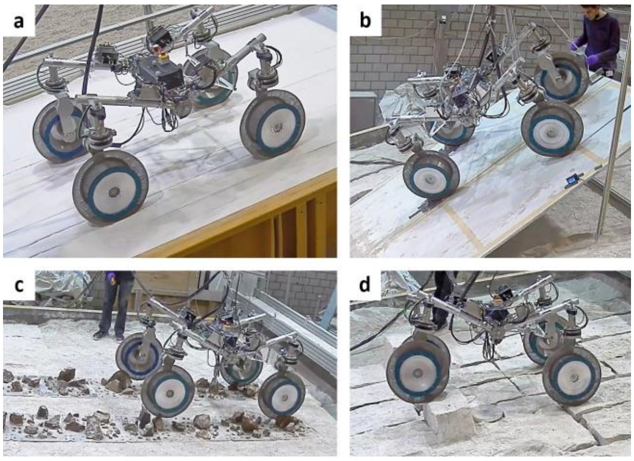

Figure 5 – Snapshots of the SFR locomotion breadboard tests: (a) loose sand slope, (b) static stability, (c) rough terrain traversal, (d) obstacle climbing on bedrock (courtesy MDA, Beyond Gravity)

These trials provided valuable insight into the behavior of the four-wheel platform and demonstrated excellent performance, meeting and exceeding the SFR mission requirements. The rover was able to negotiate slopes greater than 20° on compacted soil and bedrock, and over 12° on loose sand. Its obstacle climbing performance was also very promising, overcoming rocks taller than 30 cm on all substrates on flat ground, then decreasing as a function of slope. A complete summary of the results can be found in [11]. Some snapshots of the tests are provided in Figure 5.

Such an incremental test approach, starting from prototypes of limited fidelity and moving towards more representative models, proved vital for the SFR development. Not only did it mitigate risk and provide insight as early as possible, but it also allowed the designers to refine and validate the models used to predict the vehicle's performance and inform design decisions.

It is thanks to the iterative design, informed by these models, that the SFR achieved a factor 5 improvement in traverse energy consumption compared to ExoMars, making it a remarkably efficient transportation system. This locomotion technology has now become attractive for various future mission scenarios, extending to any small-to-medium-sized robotic vehicle, operating on Mars and especially on the Moon. Further discussion of the SFR locomotion design can be found in [12].

6. Guidance Navigation and Control

The Guidance Navigation and Control (GNC) System on SFR draws upon a strong heritage from the ExoMars Rover. The sensors used are very similar, the basis of the algorithms for perception and hazard detection is the same, and the way of commanding the locomotion mechanisms is also comparable, despite the different number of wheels. On the other hand, some important enhancements were needed to the ExoMars GNC to accomplish the SFR mission, in particular in response to two design drivers: timeline, which requires faster traverse, greater daily range and less ground involvement, and sample tube retrieval, which necessitates the ability to accurately position the rover in the tube depot area.

Before addressing how these particular challenges were met, an outline of the SFR GNC architecture is provided, which is nearly identical to that of the ExoMars Rover [13]. The GNC algorithms run on the On-Board Computer (OBC) and include functions like perception and evaluation of the terrain to create a navigation map, path planning to plot a course through that map, trajectory control, localization and traverse monitoring to guide the vehicle along such a path. The GNC algorithms primarily interface with the following hardware:

- Navigation Camera (NavCam). A stereo camera mounted on the mast head and steered by a pan and tilt mechanism to acquire a Digital Elevation Model (DEM) of the surrounding terrain. This happens every 2.7 or 5 meters, depending on the mode.

- Localization Camera (LocCam). Identical to the NavCam, but mounted at the base of the mast. It images the terrain immediately in front of the vehicle at a relatively high frequency (0.5 Hz) to track the rover's motion.
- IMUs. Accommodated inside the rover, they consist of gyroscopes and accelerometers that measure the rover's attitude and contribute to estimating its motion.
- Locomotion subsystem. The actuators and sensors described in Section 4, plus the drive electronics that control them.

The GNC algorithms fuse information from all these sources to ensure rover safety and make decisions on its trajectory, which are then translated into commands to the Actuator Control Electronics to steer the locomotion mechanisms along the chosen path. Figure 6 provides a simplified view of the functional architecture of the SFR GNC System.

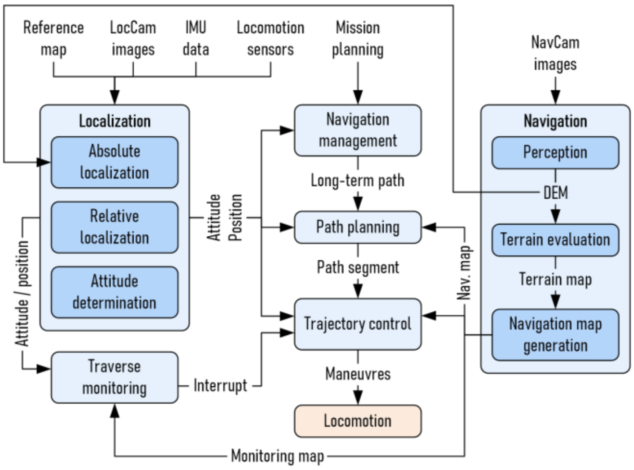

Figure 6 – Functional architecture of the SFR GNC System

As mentioned above, while the SFR GNC architecture is largely similar to that of ExoMars, a few notable enhancements were applied to meet the greater traverse demands. Firstly, since the cruise speed is more than 6 times higher than ExoMars, the frequency of sensing and commanding while driving had to increase accordingly to maintain a similar spatial cadence. A key limiting factor for the daily range of any planetary rover is the time spent stationary while mapping the terrain and planning a path through it, which is often greater than the time spent driving. On the ExoMars Rover, in its Autonomous Navigation mode (AutoNav), a Navigation Stop (NavStop) has an average duration greater than 10 minutes. On SFR, this time was reduced to under 2 minutes to improve timeline performance. These improvements were obtained using a more powerful OBC, described in Section 9, which allowed running the heritage ExoMars GNC software at a greater speed.

To further increase the net traverse speed, a new GNC mode was also devised for SFR, taking advantage of the fact that much of the terrain is already known from Perseverance's data. In this mode, the rover follows a previously assigned path, known to be on easy terrain, and performs a NavStop every 5 m instead of the 2.7 m mentioned earlier. All the safety functions remain active and, if an unexpected hazard is detected, the rover can perform avoidance maneuvers or switch back to full AutoNav mode to plan a new path.

Lastly, the need to reliably approach sample tubes required some additional GNC functions. The objective of this approach is to place the tube within the range of the vision and handling systems; therefore, it must be performed while the tube has yet to be detected by the onboard cameras. To meet the timeline, SFR has to do this autonomously, with ground intervention only foreseen in off-nominal situations. This means that SFR must be able to accurately position itself in relation to the tubes in the depot or, in fact, to the terrain around them. Once again, information from Perseverance can be used to accomplish this task, since the depot area will be extensively imaged when the tubes are dropped.

A novel GNC capability was developed to establish SFR's absolute position on the Martian terrain. This functionality is called Absolute Global Localization (AGL), and it estimates the rover's position by comparing the terrain model generated while navigating with map data stored on board [14]. Two variants of AGL were implemented: AGL-Depot (AGL-D) and AGL-Traverse (AGL-T). AGL-D uses high-resolution data from Perseverance and can establish the rover's location in the sample tube depot with an accuracy of the order of 10 cm, while AGL-T uses lower-resolution orbital imagery and can locate SFR during its traverse with an accuracy that varies depending on the quality of the reference data, typically in the order of meters.

AGL allows SFR to update its absolute position knowledge at any point during its mission, which is a particularly interesting feature, considering that the absolute localization of a planetary rover usually degrades during traverse, as the initial position is propagated using onboard sensors. Accurate positioning is typically re-established by ground control, which is a time-consuming operation, especially considering the communication delay with surface assets on Mars. AGL enables SFR to neutralize that error on board whenever needed, making it capable of operating autonomously for several sols and reaching a set location on the surface without ground intervention. This functionality is illustrated by Figure 7.

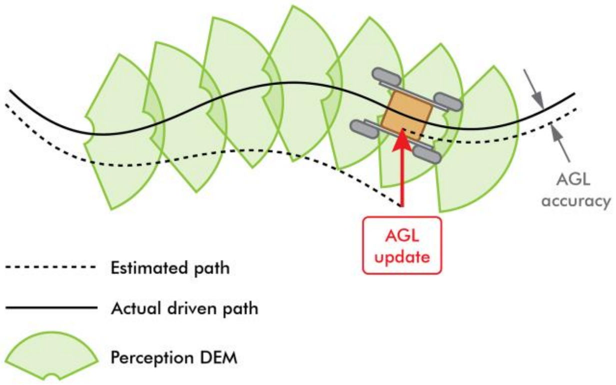

Figure 7 – Illustration of an AGL update on SFR

The performance of AGL, as well that of the overall SFR GNC, was validated successfully through field trials with a full-scale vehicle, based on the locomotion platform described in Section 4, but upgraded with GNC hardware and software. This vehicle is shown in Figure 8 during testing on a simulated mission terrain in a sand quarry in the UK.

Figure 8 – Field testing of the SFR GNC

The tests have shown that SFR not only can traverse significantly faster than previous Mars rovers and meet its timeline, but also that it is able to reliably update its absolute localization with an accuracy of up to 10 cm (depending on the quality of the reference map). In one endurance test, SFR drove autonomously for over 300 m in one day, getting valid AGL solutions throughout the drive. The test was halted at the end of the day, but, given time to recharge its batteries, the rover would be theoretically able to do this indefinitely, as long as it remains within the boundaries of the onboard reference map.

This localization technology is clearly attractive for future rover missions as it avoids time-consuming iterations with ground control and maximizes the daily range of the vehicle. AGL does not make direct use of orbital assets (unlike satellite navigation or ranging) and the reference map can come from a variety of data sources, including orbital or aerial imagery, as well as other planetary vehicles. Its performance is essentially driven by the quality of the input map and the presence of recognizable terrain features, and it can be applied to any rocky planetary body. AGL enables mission controllers to simply choose targets on a map, which could be especially desirable for highly automated tasks like mining, construction or deployment of hardware. Further information on the design of the SFR GNC System can be found in [15].

7. Sample Tube Acquisition

The identification and retrieval of sample tubes is one of the most novel and critical functions in the SFR mission. Its design is strongly influenced by the need to be robust to the unstructured environment in which the tubes are placed, with terrain material that could contaminate the tubes, limit their visibility or reachability. While traverse operations are constrained both in energy and time, the energy demand during sample tube acquisition is generally benign, so this operation is mostly limited by the time available during the day. In response to this constraint, a high degree of autonomy was developed to improve the duration and robustness of the sample acquisition functions. The robotic payload that performs these functions is the RSTA Acquisition System (RAS). Its architecture is composed as follows:

- Vision system, consisting of the NavCam on the rover's mast, the RSTA Detection Camera (RDC) on the wrist of the robotic arm, and the Vision-Based Detection Software (VBDS) running on the rover's OBC
- Arm and Gripper Subsystem (AGS), composed by a robotic arm on the front of the rover, its end effector, a re-grip station and the AGS control software, running on the OBC
- Tube storage, a structure containing 30 slots to accommodate sample tubes
- Acquisition Management Software (AMS), in charge of the end-to-end acquisition sequence, also running on the OBC

It is highlighted that certain equipment onboard the rover is shared with the RAS. As noted above, the NavCam is also part of the GNC System, and all the RAS software runs on the central OBC. Furthermore, the Actuator Control Electronics (ACE) that control the robotic arm also control all other mechanisms on board. The use of shared resources complicates interfaces and is often not as performant as fully tailored hardware, however, planetary rovers are severely mass-constrained systems and trade-offs like this are not uncommon. Figure 9 offers a closer view of the front face of the vehicle with the robotic arm deployed and other RAS elements annotated.

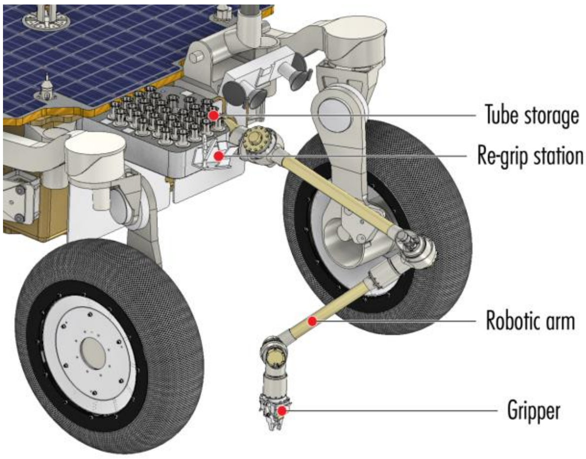

Figure 9 – Front face of the rover with RAS components

The RAS is engaged once the rover has reached the sample tube depot and, thanks to the AGL-D functionality described in Section 5, has parked within a few tens of centimeters of a tube to be retrieved. The first detection attempt is performed using the NavCam. The stereo images are fed to the VBDS, which estimates the position and orientation of the tube using a semantic segmentation algorithm based on a convolutional neural network. The key challenge for this software is related to the terrain, since it must recognize the tube amongst various surface features and possibly with significant dust coverage, due to the long time that the tube could have spent exposed to the environment. Furthermore, the VBDS is also designed and trained to be robust against various illumination angles and shadows on the scene. Lastly, its computational complexity is strictly constrained, as it must execute in a reasonable time (an allocation of a maximum of 10 minutes, to respect the timeline) using the limited on-board processing power.

NavCam-based detection can establish the position of the tube with an error of ±26.6 mm along its axis and ±6.6 mm in a direction orthogonal to its axis. While this is suitable for most cases, in certain situations the tube could be close to terrain features, such as rocks or local changes in elevation, which could restrict access and necessitate a more accurate approach. For this reason, the RDC was introduced on the manipulator's wrist to provide close-up images of the tube. These are expected to improve the accuracy of VBDS results and enable ground control to troubleshoot particularly challenging approaches.

As an example, Figure 10 shows a sample tube dropped by Perseverance in the depot created in January 2023. The assembly is approximately 190 mm long. This is one of the 30 units that the RAS was designed to retrieve. This particular one is placed on rather benign, flat terrain, thanks to a careful selection of the depot site.

Figure 10 – Sample tube dropped by Perseverance on Mars (credit: NASA / JPL-Caltech)

Once the tube's position and orientation have been established by the VBDS, the robotic arm is commanded to approach it. The SFR robotic arm is a 6-Degrees-Of-Freedom (DOF) manipulator with a reach of approximately 1400 mm. Like other critical components on board SFR, the arm takes advantage of existing technology, in particular, the DExtrous LIghtweight Arm for exploratioN (DELIAN) prototype, developed by Leonardo to operate in the Martian environment [16]. The arm uses two sizes of joints: a heavy one for the first three joints from the base, that hold most of the limb's weight, and a light one for the last three joints. Both joints use Maxon DC motors (DCX 22L on the heavy ones, DCX 14L on the light ones) connected to three-stage planetary gearboxes and Harmonic Drives on the outputs. Redundant, single-speed pancake resolvers were chosen as position sensors. The heavy joints also include an active friction brake, similar to that mentioned in Section IV, to prevent the arm from collapsing if power is removed while extended.

As anticipated, a key challenge for tube pickup is posed by the terrain, which can obstruct access or prevent correct grasping. To address this, the gripper's fingers are designed to be nimble, able to cut through accumulations of sand, but also robust against contact with hard ground. The fingers are driven by another Maxon DCX 14L motor, connected to a three-stage planetary gearbox and a worm gear. The gripper is equipped with various sensors, such as strain gauges and micro switches, to verify that the tube is correctly grasped and is not subject to excessive loads. The grasping is performed on the cylindrical body of the tube, also called "shaft", which is a relatively large and accessible feature. A prototype of the SFR gripper is shown in Figure 11. This article underwent testing at AVS Spain (in lab conditions) and Airbus UK (in simulated terrain conditions).

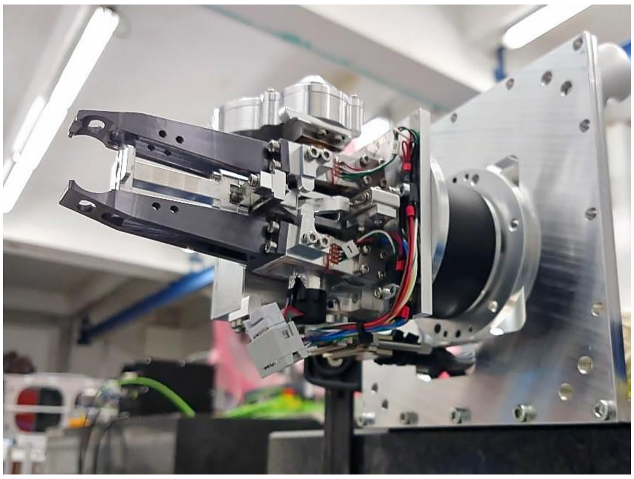

Figure 11 – Prototype of the SFR gripper (credit: AVS)

The tubes must be placed in the storage assembly with their “heads” (i.e., the ends with larger diameter) pointing upward, so that they can be subsequently grasped by the lander’s robotic arm. Inserting the tubes in their storage slots with such orientation necessitates a change of grip, which is performed by temporarily placing the tube on a re-grip station. The storage slots are equipped with metal clips that engage with the tube to ensure it is kept in place during traverse. However, this means that the clearance around the tube during insertion is limited. Such tight clearance led to challenges in the insertion motion, which was on the edge of the arm’s performance in terms of positioning accuracy.

To solve the problem, the introduction of a force/torque sensor on the arm’s wrist was proposed to allow detection of contact and trajectory correction before the mechanical load can exceed the allowable level for the tube. The sensor would also be useful for other functions, such as detection of contact with the ground or general load protection of the tube throughout the manipulation sequence. It must be noted that the addition of this sensor has a significant impact on the mass of the robotic arm and the amount of harness routed along it. Its implementation and the impacts on the system have only been preliminarily assessed at this time.

The operations described above take place in a constrained timeline, limited in the morning by the time to warm up the rover and in the evening by the availability of sunlight for visual recognition and by the need to enter sleep mode for the night. This constraint pushed the acquisition sequence to be highly autonomous, as ground commanding of spacecraft on Mars imposes heavy time penalties because of the communication delay and timings in the orbital relay chain. Therefore, ground involvement must be minimized to meet the mission timeline. SFR is thus designed to execute a tube acquisition sequence in complete autonomy and, once done, it can also move to the next tube and repeat the process for all the tubes that have been flagged for retrieval.

To further reduce reliance on ground control, the AMS is programmed to recover autonomously from various failure conditions. For example, if visual identification of the tube failed, the rover could acquire several images with different exposures or even drive around the tube location to provide a different angle to the camera. If all these strategies fail, the rover would send a request for ground intervention, along with images and data on the event. Even in this case, SFR would not stop and wait: for the sake of time, it would move on to the next tube and come back to the problematic one once ground has uploaded commands for an alternative strategy.

Preliminary tests have demonstrated the performance of key elements of the RAS, such as the AGS [17], and system-level testing is underway at the time of writing. Many RAS technologies are rather new and specific to the SFR mission. However, future planetary rovers might need a similar ability to identify and manipulate equipment autonomously, for example, for deployment of hardware and construction of outposts. It was therefore chosen to continue maturing these technologies through field testing despite the cancellation of the mission.

8. Structure and Thermal Control

The SFR body structure largely relies on consolidated materials and technologies previously implemented on the ExoMars rover. The main frame is a rectangular parallelepiped made out of Carbon-Fiber-Reinforced Polymer (CFRP), open on the top and bottom faces to integrate components inside. Its dimensions are heavily constrained by the accommodation on the lander, and they are approximately 800 mm in length, 750 mm in width and 420 mm in height. The underbelly panel, top-deck panel and deployable solar panels are all sandwich panels with aluminum honeycomb core and CFRP skins.

Beyond providing integrity to the vehicle and carrying all primary loads, the body structure also creates a thermally-insulated enclosure to protect sensitive components, such as avionics and batteries. In order to do this, its outer surface is covered in goldized Kapton to reduce its infrared emissivity and its inner volume provides a “gas gap”, i.e., an envelope around the electronic equipment that is filled by the thin Martian atmosphere. The rover body is fully sealed according to planetary protection rules, with the exception of specialized High-Efficiency Particulate Air (HEPA) filters that allow venting while preventing the egress of any contaminating particles or microbial life. All of these are relatively mature technologies, but their successful implementation in such a harsh environment is not trivial, especially with respect to material compatibility and thermoelastic distortion caused by the extreme temperature range.

Concerning the thermal control system of the rover, the most demanding challenge is to balance the ability to survive the cold nights with the need to sustain high-power operations during relatively warm days. Unlike ExoMars, SFR does not have Radioisotope Heater Units (RHU) on board and can only rely on battery-powered heaters to maintain its internal temperature at night. This choice was made to avoid the complexity of handling radioactive materials and minimize the risk of any associated delays. Good insulation is therefore essential to contain the energy demand on the battery. On the other hand, SFR is a rather powerful machine and can dissipate a significant amount of energy while traversing, which would quickly overheat a well-insulated system. To offload some of that heat, two propylene loop heat pipes connect a central thermal bus, where the electronic units are mounted, to external radiators. These are a direct reuse of the ExoMars loop heat pipes [18]. Furthermore, highly dissipating Actuator Control Electronics have been moved to the outside of the vehicle to mitigate this issue, as described in Section VIII.

It must be noted that the heat rejection performance of the radiators is rather limited during the day, when the environment is relatively warm. To further reduce the risk of overheating during prolonged traverse, the rover uses a novel solution for Mars, but not unknown to other spacecraft: Phase Change Material Capacitors (PCMC), i.e., thermal energy storage based on the latent heat of a particular substance. The SFR PCMCs are two containers, each filled with 2 kg of hexadecane (whose melting temperature is 18°C) and able to store almost 1 MJ of thermal energy in total. The PCMCs melt during the day to absorb peaks of power, for example, during traverse, and then solidify again in the evening, when their heat is distributed into the thermal bus and extracted by the loop heat pipes.

One last peculiar characteristic of the SFR thermal control is that the warm-up of external components and actuators, rather than relying primarily on electric heaters, aims to use the warmth from the environment as much as possible, with minimal contribution from heaters. This passive warm-up strategy serves, once again, to minimize energy expenditure. However, it also means that the external hardware becomes operational rather late in the day (typically late morning or midday). This is, in fact, one of the limiting factors that constrain the daily operational time and dictate a high traverse speed to fit the required distance into that time.

While the technologies used in the structure and thermal control of the rover are not new by themselves, their combination led to the design of a highly efficient system, demonstrating the feasibility of night survival without radioactive materials and the benefits of PCMCs for high-power operations.

9. Mechanisms and Control Electronics

There are four major mechanisms on board SFR, some of which have already been described in previous sections. Each of these mechanisms has multiple actuators that need to be controlled. The actuators can be divided in two main categories: electric actuators (driven by electric motors) and Hold-Down and Release Mechanisms (HDRM, structural restraints used to stow appendages and survive launch loads, then released using a separation device). The onboard mechanisms and their actuators can be summarized as follows:

- Locomotion mechanism: 8 electric actuators, 4 HDRMs.
- Arm and Gripper Subsystem (AGS): 7 electric actuators, 2 HDRMs.
- Deployable mast: 3 electric actuators, 1 HDRM.
- Solar array mechanism: 3 electric actuators, 4 HDRMs.

In addition to the above, 4 body HDRMs are used to disconnect the rover from the lander during its deployment on Mars and are not strictly part of a mechanism perimeter, but rather belong to the rover body structure. All of these devices need to be controlled by specialized electronics. On other types of spacecraft, each mechanism would have its own, dedicated drive electronics, optimized for its specific needs. However, on a small rover like SFR, mass and volume constraints make this approach unworkable. Centralized Actuator Control Electronics (ACE) were developed for this purpose and are accommodated inside two cold-redundant units on the sides of the vehicle (see Figure 1).

From each unit departs a considerable amount of harness to reach all actuators and sensors on board. The complexity of these interconnections can be observed in Figure 12, which represents the links coming from one ACE unit (the other one would be exactly mirrored). Furthermore, the figure only shows actuator control and sensor interfaces, while the ACE manages heaters and temperature sensors as well. As such, the complete diagram would be far more intricate.

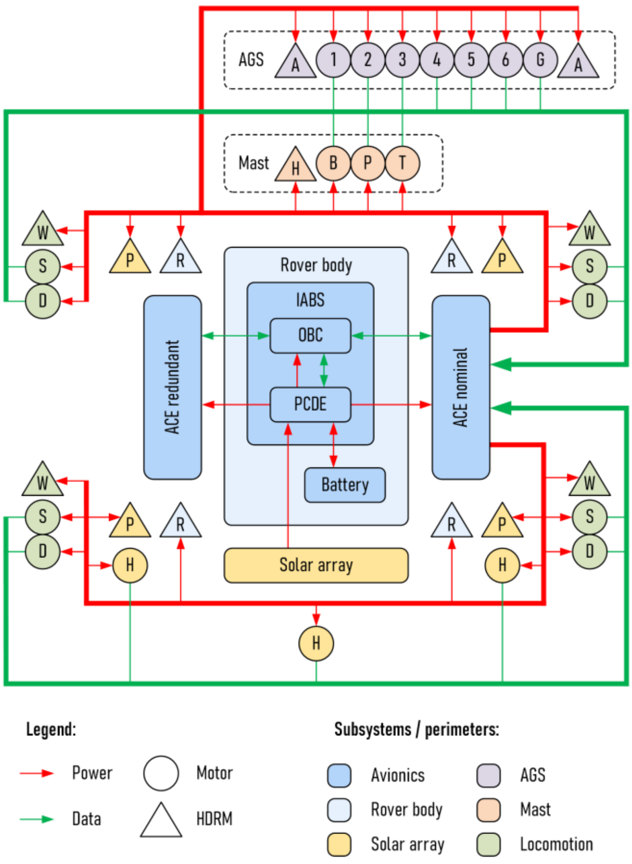

Figure 12 – Diagram of the ACE connections

All the ACE harness must be routed mostly outside the rover, from which derives one important consequence: electrical conductors are generally also good thermal conductors and would leak an extensive amount of heat out from the electronics. The energy limitations on SFR make it unaffordable to keep these electronics warm. Thus the ACE were placed outside and designed to withstand the cold Martian night without any survival heating. This also reduces the power dissipation inside the rover, alleviating the risk of overheating, as described in Section 7.

Enduring exposure to the Martian environment is a significant challenge for electronics design. It necessitates extremely robust components and materials that can withstand daily temperature excursions between -125°C and the maximum operating temperature, which, for some parts, is over 80°C. The qualification of electronic devices for this environment is also a complex and onerous endeavor, as it can only be done by exposing the hardware to a simulated lifetime profile of hundreds of thermal cycles. These tests need thermal chambers that can reach extremely cold temperatures (usually relying on liquid nitrogen) and, even if accelerated, can last several months.

While having a central electronic unit saves mass and volume, it poses another issue for the electronics design: it requires them to interface with very different mechanisms, each with its own needs. To address this problem, the ACE interfaces were standardized, allowing only certain devices to be used in the mechanisms, for example:

- Motors: limited to Maxon DCX 14L, 22L or 32L
- Rate sensors: only Maxon MR-32 encoders
- Position sensors: resistive potentiometers or single-speed resolvers
- HDRMs: either EBAD Frangibolts or EBAD Non-Explosive Actuators (NEA)

This approach allowed the use of a relatively small set of circuit designs, which are then repeated as many times as required by the mechanisms interfaces. Containing the number of electronic components also alleviated the cost of their qualification. The implementation of this technology on SFR, strongly based on ExoMars heritage, demonstrated that centralized control electronics are a viable option for mass-constrained planetary rovers. The standardization of mechanisms interfaces proved to be an essential part of this plan, and particularly advantageous if done early, even at the cost of constraining the choice of actuators and sensors. Nonetheless, if the electronics are exposed to an extreme thermal environment like that of Mars, their design and qualification should be treated as highly critical tasks (a lesson learned in the ExoMars qualification and applied in the early stages of the SFR development).

10. Power, Avionics and Telecommunications

As introduced in Section 3, SFR is a purely solar-powered system. The solar panels on the top deck generate approximately 210 W on Mars at noon at the Beginning Of Life (BOL), down to 120 W at the End Of Life (EOL, accounting for ageing, dust obscuration and potential string failure). The solar array is composed of a total of 36 strings of 18 solar cells each. The cell technology is Azur Space 3G30, already used on ExoMars [19], which provides a BOL power generation efficiency of 30%. For energy storage, a built-to-print copy of the ExoMars battery is used, taking full advantage of the already consolidated technology [20]. This is a package of 56 SAFT MP 76065 XTD Li-ion cells, for a total BOL capacity of 1140 Wh and an operational voltage range between 21.0 V and 29.4 V.

The SFR core avionics generally use ExoMars technology or its direct evolution [21]. A new packaging is implemented on SFR, which merges the Power Conditioning and Distribution Electronics (PCDE) and the On-Board Computer (OBC) into a single unit, called the Integrated Avionics Box Subsystem (IABS). These elements are also depicted in Figure 12. The IABS is organized in a modular way, with a stack of several circuit boards connected to a motherboard. Redundancy is achieved by duplication of boards or internal redundancy where possible.

The main modules contained inside the PCDE section are the following:

- Solar array regulator, controlling the input from the solar array into the power bus or the battery
- Battery management module, controlling battery charging and battery disconnection if the charge gets too low
- Latching Current Limiters (LCL), distributing power from the primary bus to all users
- Heater drivers, activating heater channels inside the rover and on the ACE

The main modules in the OBC section are the following:

- Telemetry, telecommand and reconfiguration module, managing telemetry and command packages and keeping onboard time
- Analog and bi-level interface, converting analogue signals into digital telemetry
- Processor module, a radiation-hardened LEON2 SPARC V8 processor operating at 70 MHz, accompanied by 512 MB of Synchronous Dynamic Random-Access Memory (SDRAM)
- Co-processor module, a radiation-hardened GR740 system-on-chip featuring a quad-core LEON4 SPARC V8 processor, operating at 250 MHz
- Mass memory, a 43 GB flash memory chip

While most of these components are rather consolidated and similar to ExoMars, a notable advancement in the OBC is provided by the use of a new co-processor for the most computationally heavy tasks, such as image processing for GNC and VBDS. The introduction of this more powerful processor allows SFR to achieve a greater net traverse speed and identify tubes faster, thus respecting its strict operational timeline.

The PCDE is sized to distribute power according to the demands on board the rover. The idle power of the avionics is typically quite low (between 20 and 25 W, depending on the mode). RAS operations are also benign, with the arm consuming approximately 11 W during motion, a similar figure for the mast motion and, while the consumption for image processing has not been quantified yet, it is expected to be of comparable magnitude. System warm-up can be more power-intense, depending on the chosen schedule (i.e., how early and how quickly the components are heated), but usually under 50 W. The most demanding power requirement is certainly that of the locomotion subsystem. The mechanism itself can draw approximately 80 W on a benign terrain and 160 W on a difficult terrain. In some extreme scenarios, such as actuators developing maximum torque against a large obstacle, the power draw can reach 500 W. Such peaks would be rare and last less than 5 seconds, but nonetheless they represent the sizing case for the power distribution electronics.

The energy limitations that characterize the SFR mission have driven the introduction of another notable feature into the avionics. Since surviving the night on battery power is a significant challenge, the IABS adopts a carefully engineered “sleep pattern” during the night. In this mode, power is removed from most of the other components listed above, maintaining only a handful of critical LCLs and heater drivers for survival. This also deactivates the whole OBC, except the telemetry, telecommand and reconfiguration module that keeps onboard time and wakes up the rover with a pre-programmed alarm or if a “hail” radio signal is received. The power consumption of the IABS in this sleep mode is estimated at approximately 8 W, which is a remarkably low power for spacecraft avionics. This sleep mode allows the rover to survive the night on a limited amount of energy, while still having access to high computing power during the day, thanks to the processor and co-processor modules.

While avionics designs are usually tailored to each mission, the advancements obtained on SFR in terms of computational capability and low power consumption will likely be relevant to future planetary missions. Of particular interest is the fact that this performance was achieved with high-reliability, radiation-hardened electronics, which would be able to operate in most planetary and deep space environments.

The communication system on SFR is almost identical to that on ExoMars, using two redundant Ultra High Frequency (UHF) transceivers accommodated inside the rover body. These are connected to two compact monopole antennas on the top deck, each producing approximately 5 W of radio power output. Such communication architecture is rather compact and low-power, but has one important limitation: it can only reach Mars orbit and needs a relay to exchange data with Earth. This service is provided by the Mars Relay Network, which is formed by a fleet of NASA and ESA spacecraft in orbit around the planet. Free from the mass and power limitations of surface vehicles, they carry large, high-gain antennas to establish a radio link with Earth, typically on X-band frequencies.

Several of these spacecraft are aging and their availability cannot be guaranteed at the time of SFR’s arrival. Therefore, the rover’s communication strategy assumes only one orbital relay: the Earth Return Orbiter (ERO), part of MSR. This makes communication windows scarce, adding to the push for autonomy and requiring the vehicle to operate for a long time without ground intervention. To take advantage of all orbiter passes, SFR can also wake up from its sleep mode to communicate during the night, which is undesirable in terms of energy, but necessary in some mission scenarios.

11. Conclusion

This paper offers an overview of the key technologies developed for SFR, emphasizing those innovations that could be applied to future rover missions. It is by no means an exhaustive discussion of their technical implementation, but it aims to show how the design was shaped by specific drivers, such as the strict timeline, mass and volume constraints, energy limitations and the need to retrieve hardware from challenging terrain. Furthermore, it describes how the harsh Martian environment is itself a strong design driver.

SFR responds to its challenging requirements with a peculiar mix of heritage and novel technologies, some of which are likely to be relevant to other rover missions. For example, it has been shown how a maneuverable, high-performance and high-efficiency locomotion subsystem has been designed and tested, with extensive characterization of four-wheel planetary mobility. This technology can be applied to Mars, the Moon or other planetary bodies. The same is true for the GNC system, which, although using heritage sensors, has become faster, more autonomous and able to provide onboard absolute positioning. The GNC performance was demonstrated by successful field trials in 2022 and it was decided to perform further testing in the following years to continue improving the technology in view of future rover missions, especially to the Moon, where the required traverse pace is usually faster.

A new system for autonomous recognition and manipulation of hardware has been developed, and this, too, is foreseen to undergo further testing and refinement. While this technology was specifically developed for the recovery of sample tubes, it can be adapted to the deployment and operation of other payloads on a planetary surface. Other innovative features discussed here, like efficient thermal control with heat storage, nuclear-free night survival, compact, powerful avionics capable of low-power hibernation, could all be valuable for future planetary missions.

The prototypes developed during this program remain available for further testing, and some of them are still being used to further mature the technologies presented here. The breadboard locomotion platform shown in Figure 5 has been integrated into a full-vehicle model, shown in Figure 8. At the time of writing, this integrated vehicle continues to be used in field testing by Airbus UK for ESA to further enhance the performance and autonomy of the GNC system. A new robotic arm, gripper and cameras have been added to the platform so that sample acquisition can be tested in the field as well. This vehicle also serves as an ongoing testbed for the wheels, which are regularly inspected as they accumulate wear in a real-world setting.

The locomotion actuator breadboard models, described in Section 5, were tested and disassembled by Maxon Motor and the information gathered is being used to continue the development of key components like the friction brake and the motor encoder. The gripper, shown in Figure 11, was integrated into a larger test bench including a robotic arm, cameras, vision software, representative lighting and a "sandbox" area in which sample tubes can be placed. This setup allows the acquisition system to be tested and fine-tuned in a controlled environment, where various terrain geometries, lighting conditions and tube placements can be investigated. All these test articles, the associated activities and data gathered contribute to the preservation and further development of the technological advancements achieved on SFR.

Now that the SFR project has been stopped, and in light of the growing interest for a return to the Moon, this publication aims to broadcast these accomplishments so that other missions can build upon them. While this is only a limited summary, it attempts to provide an indication of how these engineering challenges were overcome. For one day, not too far in the future, they will have to be overcome again.

12. Acknowledgments

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- The SFR locomotion mechanism was designed by MacDonald, Dettwiler and Associates Ltd. (MDA) in Toronto, Canada
- The SFR locomotion actuators were developed by Maxon Motor AG in Sachseln, Switzerland
- The Mars Spring Tire was developed by NASA Glenn Research Center in Cleveland, OH, USA
- The Vision-Based Detection Software (VBDS) was developed by GMV Innovating Solutions, S.L. in Madrid, Spain
- The Arm and Gripper Subsystem (AGS) was designed by Leonardo S.p.A. in Milan, Italy

- The SFR gripper was designed by Added Value Solutions (AVS) in Elgoibar, Spain

Part of this research was carried out at the Jet Propulsion Laboratory, California Institute of Technology, under a contract with NASA (80NM0018D0004).

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