# EXECUTIVE REPORT

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**Introduction**:

In the realm of planetary exploration, the successful navigation of exploration rovers across distant and inhospitable terrains presents a formidable challenge. The efficacy of these rovers in conducting scientific research and expanding our understanding of celestial bodies hinges upon their ability to traverse varied. Improvement of autonomous vehicles capabilities by enhancing the Perception System is currently identified as the primary mean to revolutionize the capabilities of future exploration rovers. Central to their mission is the acquisition of stable and clear images, essential for navigating the alien landscapes they traverse. However, the inherent vibrational disturbances encountered during operation pose a formidable challenge, impeding the rover's ability to capture crisp images in real-time.

Addressing this challenge head-on, the STEADY stabilization system emerges as a beacon of innovation, poised to revolutionize the perception capabilities of exploration rovers. By integrating advanced sensors, actuators, and control algorithms, the stabilization system enables real-time adjustments in rover orientation and stability, thereby enhancing overall performance and reliability. With its innovative features and robust design, the ISS has the potential to redefine the capabilities of exploration rovers and pave the way for unprecedented scientific discoveries on distant planets and moons.

In this Executive Summary, a comprehensive overview of the project, from its inception to the successful demonstration of its capabilities through breadboard testing and ground demonstration, highlighting the key objectives, methodologies, and findings. Through this summary, we aim to convey the transformative potential of the ISS technology and its role in shaping the future of space exploration endeavors.

**Background, Objectives and First Studies**:

The European Space Agency (ESA) has identified perception as a critical limiting factor in the autonomy and efficiency of exploration rovers, particularly in the context of Lunar and Martian operations. The need for stable image acquisition during navigation poses a formidable challenge, as the inherent vibrational disturbances encountered during rover movement can degrade the quality of captured images. Presently, the conventional approach involves halting rover movement to allow mechanical vibrations to dampen—an approach that is not only time-consuming but also compromises mission efficiency.

To tackle this, ESA has initiated a project called STEADY (acronym for camera-Stabilisation to Enhance Autonomous Driving Yield), which focuses on stabilizing rover cameras to reduce blurring during movement.

The main goal of STEADY is to make rover camera images sharper while the rover is in motion. This will allow rovers to move faster without sacrificing image quality. The development of STEADY is guided by specific needs, including the compatibility (in parametric form) with different rover designs, like the Rosalind Franklin rover (formerly known as ExoMars)

Informed by a comprehensive analysis of mission context, design concept, and operational requirements, the first challenge encountered was to be able to set up an unbiased method to determine if an image quality is 'sufficient' for the navigation purpose. A metrics for the image quality definition has been identified and associated algorithms developed and validated. The definition of the metrics has enabled the generation of technical requirements, which provided the proper framework for the project, along with the typical vibration spectrum or more generally, the input motion caused by the moving rover at camera level.

Design, production and testing of physical breadboard, targeting TRL = 3 (analytical and experimental critical function and/or characteristic proof of concept) at the end of the activity have been set as the primary objectives.

**Innovative Stabilization System Overview**

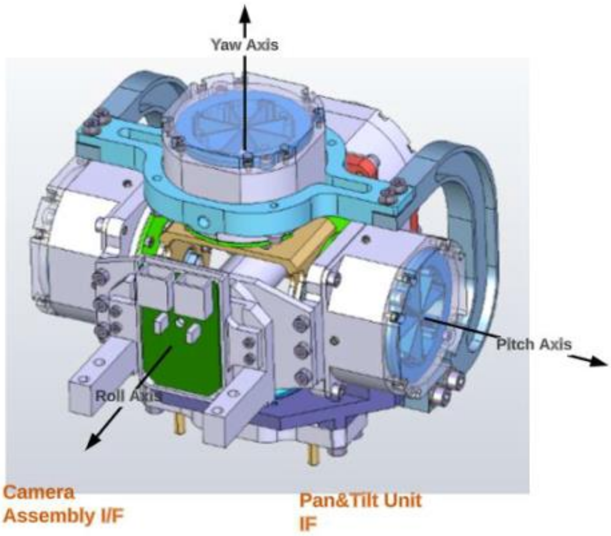
STEADY is conceived as an Image Stabilization device, and it is based on a combined active and passive vibration suppression system.

The elasto-mechanical characteristics of STEADY enables partial passive decoupling of the camera assembly of the rover with respect to the rest of the vehicle. The design is tailored to the identified bandwidth of the vibration spectrum, taking into account physical limitation and component sizing constraints.).

A model-based feedback control law enabling to compensate for resonating motion is integrated in the CSE and permits to introduce the proper damping and motion control in the lower part of the motion bandwidth (0Hz-8Hz). Working in conjunction with the passive structure of the Device, the combined stabilization system has been designed to meet the identified performance requirements.

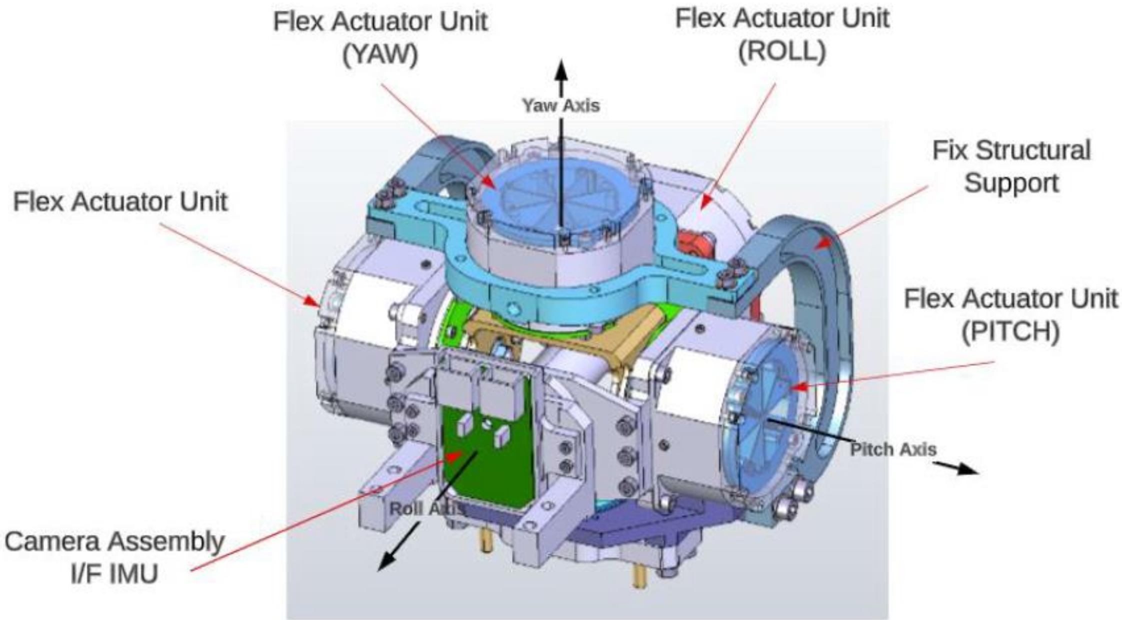
A Control System Electronics implements the monitoring and control features, enabling to read the IMU data, store the data, filter and process the relevant information and, by implementing the process level control loops, feedback the LAT (Limited Angle Torquer) torque setpoints.

Different Operational Modes are available: Monitoring, Data Storage, Initialization (health checks) and Stabilization modes.



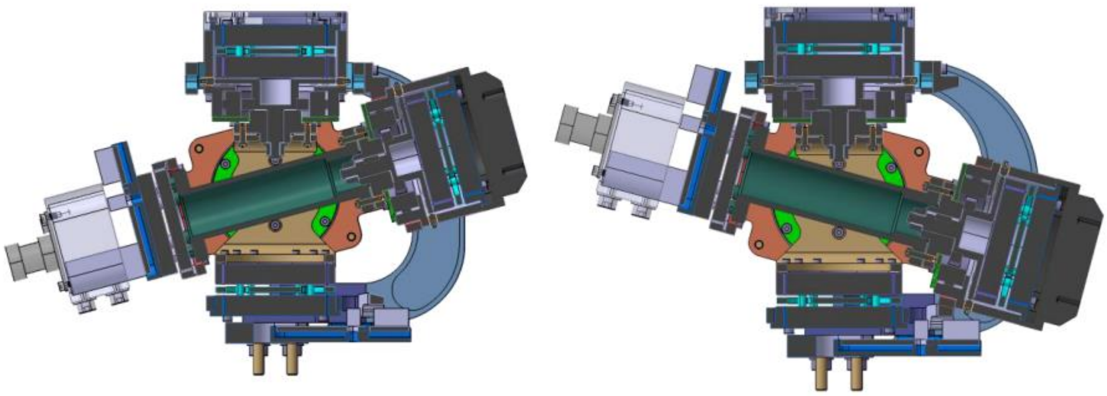

The Device design is based on s based on a hybrid 3-axis concept solution. The axes are perpendicular to each other and nominally intersect in the Center of Mass of the corresponding assembly, in order to limit the torques induced by linear accelerations and gravity. Each axis is equipped with a specially design pivot capable to provide a certain dynamic decoupling. This is achieved with two means:

- high frequency (>5Hz) motions are naturally damped by the elastic properties of flexural elements connecting one stage to the next. The elasticity range has been selected in order to comply to several constraints associated with the manufacturability of the flexure (radial stiffness, axial stiffness, structural integrity during operations, minimum thicknesses of parts, encumbrance and form factor) and the controllability
- low frequency range are handled in conjunction of the elastic response of the structure and stabilizing torque generated by the actuators in sub-units called 'Flex Actuator Units'




Embedded IMU's provide information on the state of motion of the Device and in particular on the state of motion of the lower interface (P&T unit) and the upper interface (Camera Assembly). These information are processed in a dedicated Control System Electronics, which in turns provides real-time set point of the 3 actuators.

The combined action of the reduced bandwidth control system and the large bandwidth of the structure is designed to meet the motion requirements.



A key technological component is called 'Flex Actuator Unit'. This core element enables several functions and allows the STEADY unit to fulfil its primary purpose, by adjusting the angular joint position and speed. The FAU is an electro-mechanical assembly that provides dynamic decoupling and control capabilities; this integrated design solution is constituted by

- Flexures (customized and optimized), providing the passive decoupling and structural functions;
- Limited Angle Torquer (LAT), proving active feedback to the joint

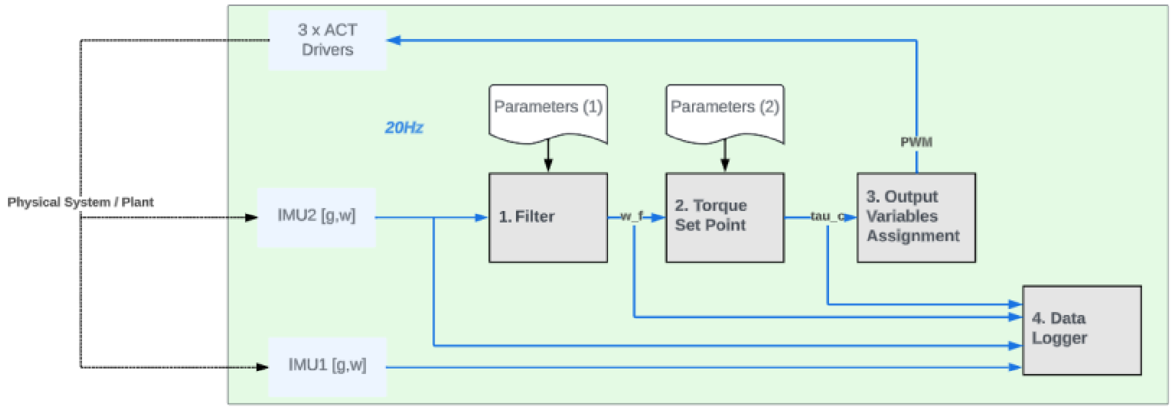
- Housing and interfacing elements (mechanical fixation and protection)

LAT's provide nearly zero cogging, thus limiting the interference with the flexure capabilities. LAT's are mounted in parallel to the flexures within the Flex Actuator units.

Flexures design is highly customizable, and, via dedicated proprietary algorithms, its design can be optimized to the specific application in compliance with the relevant constraints (performance, manufacturability, interfacing).


A dedicated Control System Electronics (CSE) has been designed, built and tested to support breadboarding and demonstration activities. The CSE includes microcontrollers, motor drivers and Inertial Measurement Units electrical interfaces. Monitoring and control functions are executed by the CSE.

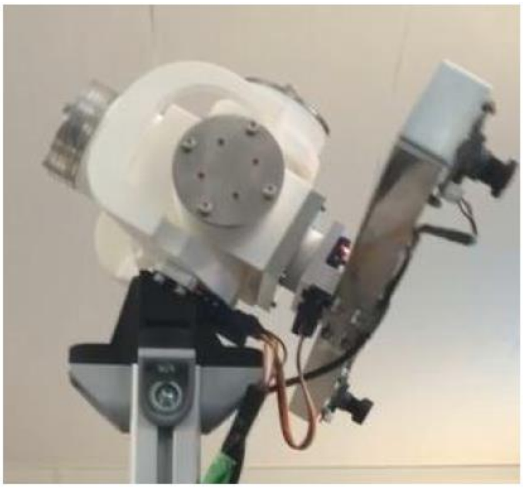
The Process Control Algorithm is executed by the microcontroller, and it has been coded in C++ (Arduino IDE). The closed-loop control adjusts the motor driver set-points based on processed data coming from the sensors (high and low pass filtering in the state observer)




Aside from the STEADY unit described above, a 'dummy' unit has been manufactured in order to support verification and demonstration activities. Purpose of the unit is to provide a well-known engineering reference of non-stabilized test cases, i.e. rigid fixation of the stereo cameras on the Rover mast.

The Dummy is design to match the inertia properties (mass, moments of inertia, at +/- 5%), and the mechanical interfaces (connections with camera assembly and with Pan &

Tilt unit). It is equipped with integrated IMU to monitor accelerations and angular rates during certain phases of testing.



A dedicated testbed has been developed, assembled and tested to be able to reproduce the simulated vibration environment that has been recorded from un-stabilized Rover runs in different terrain conditions (flat, pebbles, tiles) and different speeds. This testbed primarily consists of a Stewart Platform (6 controlled degrees of freedom), electronics equipment for power supply, a portable laptop for data acquisition and platform control, and a mock-up of the rover mast (structure) holding the stereo camera assembly. The trajectory data can be loaded and executed, thus exposing the camera assembly to the desired linear accelerations and/or rotations. The acquired images can be post-processed to define their level of stabilization or 'blurriness', based on a validated algorithm.

Due to the importance of being able to assess the end-goal system performance via the image quality, a specific metric has been identified, studied and refined to be able to rank and classify images based on a non-subjective judgment. The developed algorithm targets the blurriness of an image and predicts a 'quality score' in the form of a numerical value.

Different mounting configurations have been studies and implemented in the design and testing activities, depending on the specific purpose of the project phase.

- STEADY Dummy mounted onto the Testbed: this configuration enable benchmark testing for non-stabilized solutions and controlled motion environment
- STEADY mounted onto the Testbed: this configuration permits testing and verification activities in controlled motion environment, with direct comparison made possible with the non-stabilized solution. Both CSE and Device are installed on the Testbed to expose all equipment to the simulated vibration environment
- STEADY Dummy mounted on the Test Rover (HDPR), for reference runs (non-stabilized) during Demonstration activities
- STEADY mounted on the Test Rover (HDPR), for demonstration runs. Electrical, mechanical, accessibility and spatial interfaces are secured for proper operations

## Breadboard Testing

After assembly and component-level checks, and once the Testbed and support equipment has been assembled and commissioned, the breadboard has gone thorough a comprehensive test campaign, aiming at verifying that the foreseen design features are respected and that the requirements are met.

The methodology consisted in executing a series of planned 'Experiment Sequences' with the Testbed, aiming at exposing the unit to the most demanding conditions both in terms of structural integrity and in terms of motion intensity.

The Experiment Sequences have been extracted from a series of test data acquired directly from the rover, consisting of: 1) accelerations and angular speeds measured at camera level, and 2) camera images. For each run (data set) a specific operation condition is known (rover mean speed, terrain type). The sequences differ in terms of angular speed range, power index and spectral content, trying to cover as much a possible realistic operational condition.

| | CAMERA I/F (Pan&Tilt Unit interface) | | | | |
|---|---|---|---|---|---|
| | Acceleration (Spectral Density) | | | | |
| | 0Hz-1Hz | 1Hz-2Hz | 2Hz-5Hz | 5Hz-30Hz | 30Hz-62Hz |
| UC2.1 | 4.21 | 4.08 | 3.55 | 3.48 | 2.95 |
| UC2.2 | 7.90 | 8.38 | 7.80 | 7.02 | 4.21 |
| UC2.3 | 14.51 | 12.16 | 9.83 | 10.84 | 6.54 |
| UC2.4 | 5.58 | 7.16 | 5.63 | 4.97 | 3.57 |
| UC2.5 | 9.01 | 9.17 | 8.52 | 7.70 | 5.26 |
| UC2.6 | 18.02 | 12.21 | 12.59 | 11.52 | 7.58 |
| UC2.7 | 4.22 | 5.67 | 4.08 | 4.40 | 3.65 |
| UC2.8 | 12.37 | 11.70 | 9.84 | 11.22 | 8.39 |
| UC2.9 | 22.50 | 16.63 | 14.87 | 14.45 | 11.60 |

| | CAMERA I/F (Pan&Tilt Unit interface) | | | | |
|---|---|---|---|---|---|
| | Angular Speed (Spectral Density) | | | | |
| | 0Hz-1Hz | 1Hz-2Hz | 2Hz-5Hz | 5Hz-30Hz | 30Hz-62Hz |
| UC2.1 | 2.27 | 1.92 | 1.17 | 1.04 | 0.72 |
| UC2.2 | 3.67 | 2.38 | 1.97 | 1.81 | 1.07 |
| UC2.3 | 4.47 | 3.56 | 2.70 | 2.43 | 1.63 |
| UC2.4 | 2.14 | 2.95 | 2.19 | 1.31 | 1.12 |
| UC2.5 | 3.32 | 3.06 | 2.72 | 2.05 | 1.45 |
| UC2.6 | 5.74 | 3.77 | 2.86 | 2.64 | 2.05 |
| UC2.7 | 2.31 | 2.37 | 1.60 | 1.42 | 1.00 |
| UC2.8 | 5.03 | 4.25 | 4.19 | 3.21 | 2.29 |
| UC2.9 | 6.92 | 4.08 | 4.46 | 3.21 | 2.49 |

*Figure 1: power spectral density of the measured total acceleration (left) and angular speed (right) at the Camera I/F, for different use cases.*

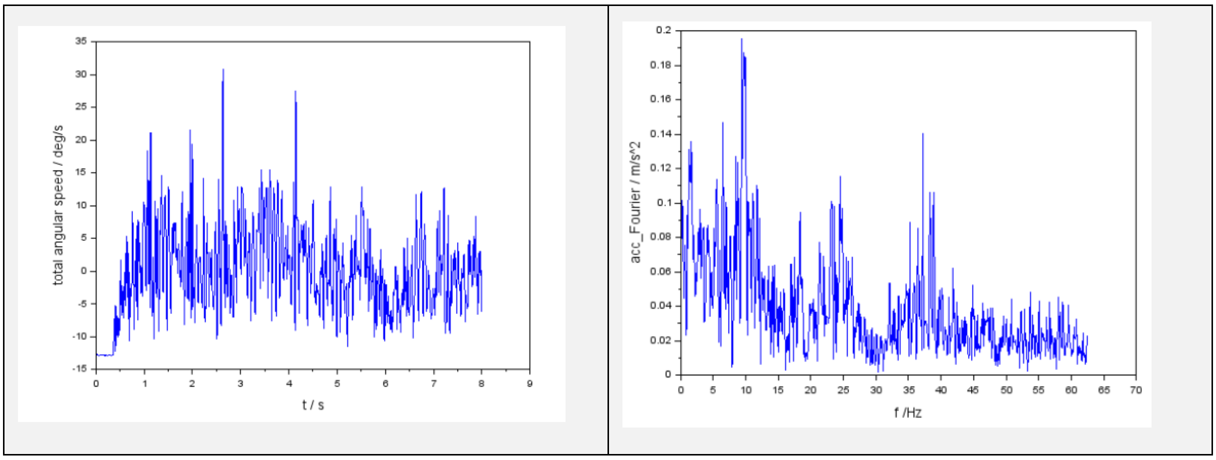
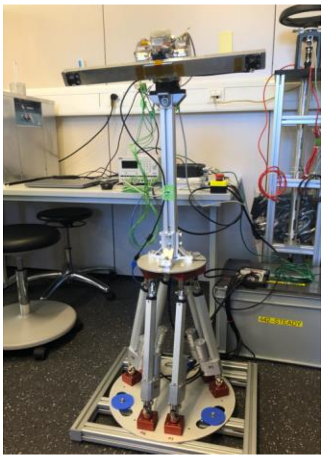



*Figure 2: Examples of time-dependent evolution of Camera I/F total angular speed as a function of time (left) and spectral content of acceleration (right)*

Basic sinusoidal motion on each individual axes were followed by 'Test Case' sequences, reproducing as close as possible – in relation to the Stewart Platform capabilities – the recorded rover motion. In order to support the claimed conclusions that STEADY has a beneficial effect on the image stabilization, two main steps needed to be taken:

1. The motion is first executed using the non-stabilized configuration, that is with the Dummy. This provides a set of data (images, accelerations) that constitute the reference point.
2. The same motion sequences are then repeated with the stabilized (STEADY) configuration, leading to a second set of data.

The comparison analysis between the two sets has then been made possible, showing the improved quality both visually and via the quality ranking algorithm.



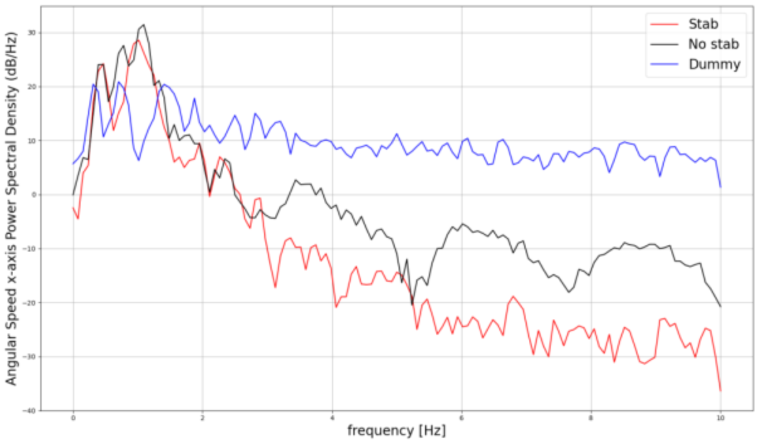



*Figure 3: Angular Speed Power Spectral Density Comparison without stabilization ('Dummy') and with active STEADY stabilization*

The ultimate goal of the system is to improve image quality, and the analyses of the test data confirm the thesis as the image quality is systematically improved when STEADY is included in the test set-up, with the exception of a single case. After meticulous analysis, it has been found that that specific test case was exciting the unit near its major resonance frequency with significantly higher amplitude than was initially intended.

Base on the overall experimental evidence it has been observed that acquired images with STEADY Device show a better quality index than the reference use case scenarios, where no STEADY is implemented.

It has also been found that in general, test cases were more aggressive in terms of motion content than the actual rover test data. This observation gives on one side important insights on how to tune and improve testbed design, and on the other provides increased confidence that the hardware can meet its originally intended purpose when exposed to a more realistic scenario, presented in next paragraph.

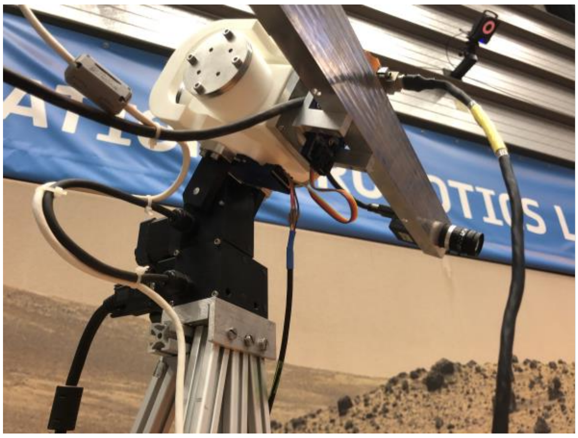
**Demonstration:**

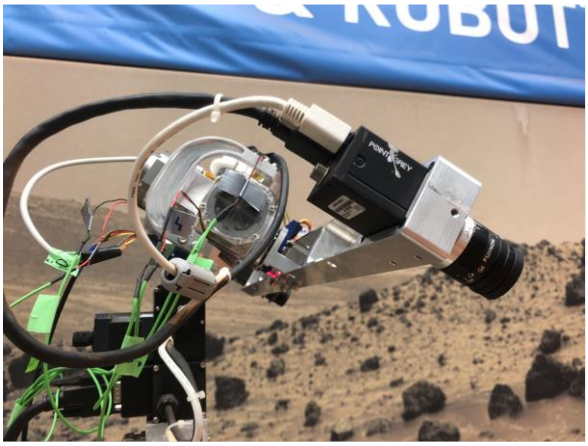
Final part of the development included a Demonstration session in representative laboratory environment. The Planetary Robotics Laboratory at ESTEC (ESA) has been selected as perfect candidate to perform the tests, as it features different terrain types and the test rover (Heavy Duty Planetary Chassis - HDPC) can be configured and guided in order to acquire the needed data. The HDPC rover has a design consisting of a 6-wheeled locomotion system with 2 rocker-bogie passive suspensions and it can only be tele-operated.

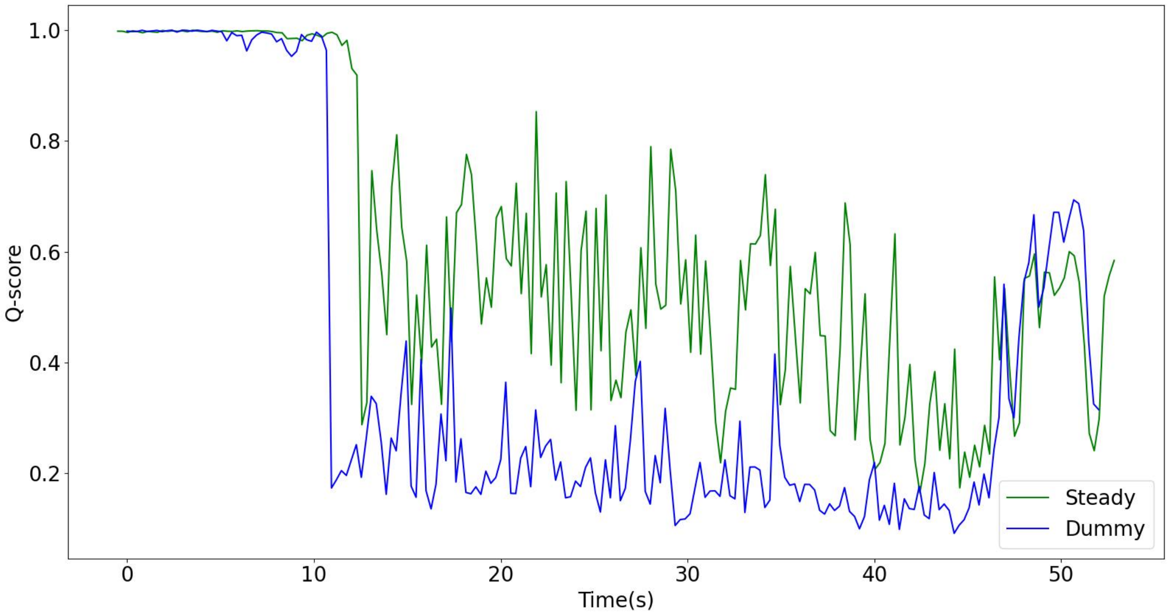
After shipping the material to the laboratory, preliminary fit and functional checks have first been executed, securing proper mounting of parts being assembled onto the rover for the first time. For the purpose of the demonstration, the Dummy unit (rigidly connecting the rover mast with the camera assembly) has then been mounted and several recordings of images and accelerations have been obtained. On top of verifying the consistency and completeness of the test procedures, the acquired data set constitutes the reference to which the follow-up test data can be compared.

The motion sequence included slow (0.1 m/s) to medium speed (0.3 m/s) as well as three different types of terrain: soft, pebbles and tiles. The sequence has been selected in order to cover most of realistic conditions encountered during fast-moving operations, while not exceeding the operational limits of the equipment both of the rover and STEADY.

The STEADY device has then been mounted and the same sequence repeated. The results showed that the objective could be met without any deviation, and the quality improvement of the images was clearly visually-detectable as well as confirmed by the quality-score index. The graph below shows an example extracted from a motion sequence executed once with the dummy (rigid) configuration (blue line) and with STEADY (green line), showing the quality index improve by more than a factor 2, and well above the target average threshold of 0.30 originally set as objective of the activity.






Q-score
Time(s)
Steady
Dummy
1.0
0.8
0.6
0.4
0.2
0
10
20
30
40
50

**Conclusion**

In the ever-evolving landscape of planetary exploration, the success of exploration rovers hinges upon their ability to navigate rugged terrains and capture clear images in real-time. The development and testing of the STEADY stabilization system mark a significant milestone in our quest to enhance the perception capabilities of these rovers.

Through a meticulous process of requirements identification and derivation, design, production, and testing, the STEADY system has demonstrated its ability to mitigate the vibrational disturbances encountered during rover movement, thereby improving image quality and enhancing overall mission efficiency. The integration of sensors, actuators, and control algorithms has enabled real-time adjustments in rover camera orientation and stability, leading to tangible improvements in performance.

Breadboard testing has provided valuable insights into the efficacy of the STEADY system, confirming its ability to consistently improve image quality across a range of motion scenarios. By systematically comparing test data from both non-stabilized and stabilized configurations, the effectiveness of the STEADY system in enhancing image sharpness and clarity has been validated.

Furthermore, the successful demonstration of the STEADY system in a representative laboratory environment underscores its potential for real-world application. The ability of the system to enhance image quality across different terrain types and motion conditions reaffirms its relevance in enabling efficient and productive planetary exploration missions.

As we look towards the future, the STEADY stabilization system stands poised to redefine the capabilities of exploration rovers, paving the way for unprecedented scientific discoveries on distant planets and moons. With its innovative features and robust design, STEADY represents a cornerstone in our ongoing efforts to push the boundaries of space exploration and expand our understanding of the cosmos.

Through collaboration and continued innovation, we are confident that the STEADY system will play a pivotal role in shaping the future of planetary exploration, unlocking new frontiers of knowledge and inspiring generations to come.