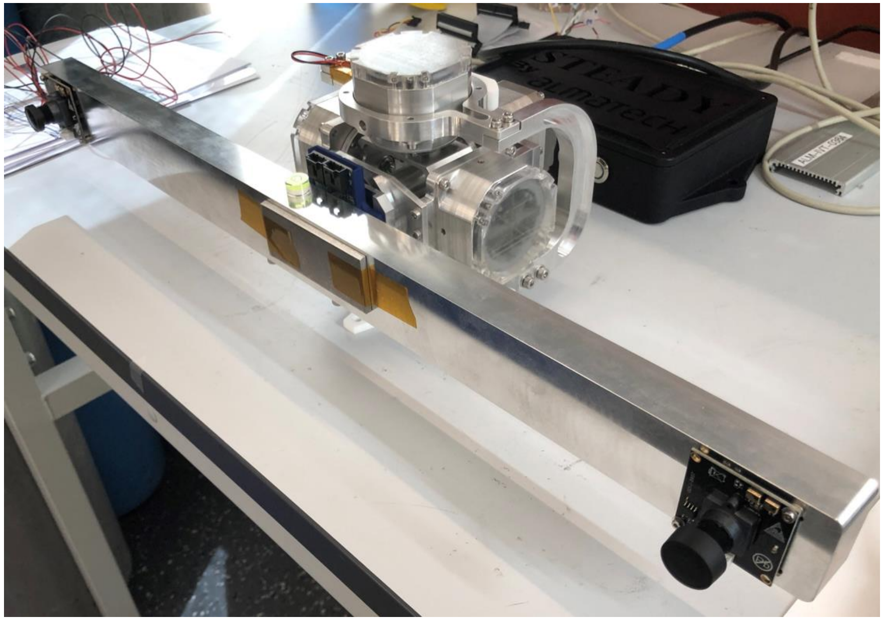
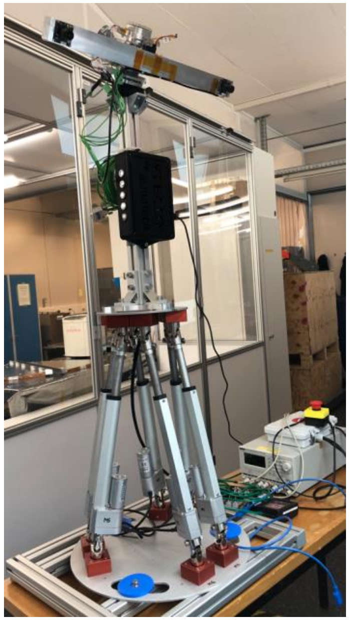
camera-STabilisation to Enhance Autonomous Driving Yield (STEADY)





STEADY
Demonstration Days at ESTEC

05.12.2023

Team

- Gianluigi Capo - Project Manager
- Stefano Nebuloni – Principal Engineer
- Oriol Lopez – Electronics Engineer
- Joel Junot – Draughtsman, Assembly
- Yoël Puyol – Analysis Engineer

Outline

- Introduction, Context & Development Logic
- Analyses of Needs
- Design Solution
- Verification Activities & Demo
- Conclusions and Open Discussion

Purpose of Activity

- Objective of this activity: improve autonomous vehicle capabilities by enhancing the 'Perception system' capabilities of the rover
  - enabling driving the rover at increasing velocities while delivering sharp images

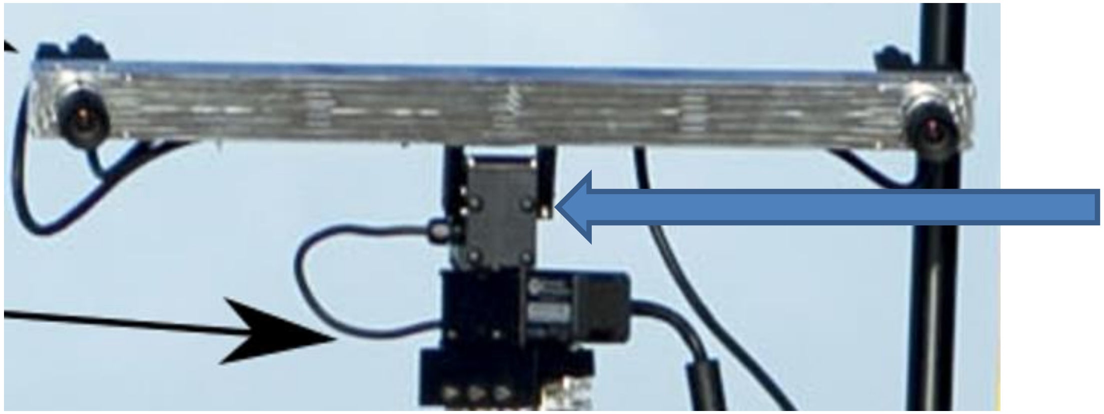
- Design, production and testing of physical breadboard

- Target TRL = 3 at end of activity

Purpose of Activity

- Alternatives:
  - Optical Image Stabilization (OIS) methods, acting either on the lenses or the support of the camera (mechanical compensation),
  - Electronic Image Stabilization (EIS), which uses complex algorithms to improve image quality

- Approach / Proposition for the TED activity:
  - Vibration reduction device to be included between the camera mast & the PanCam"

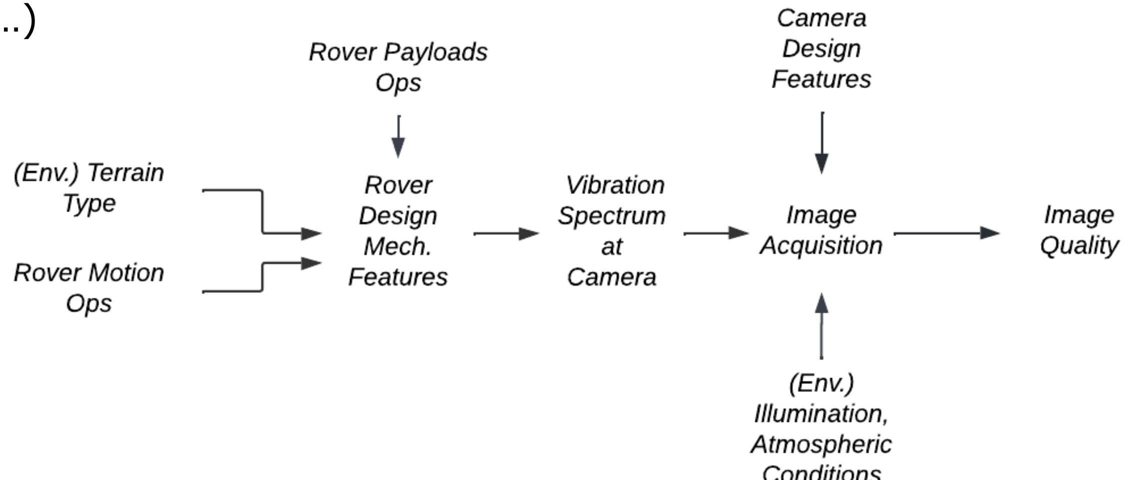


Location of STEADY: between the PanCam assembly & the Pan-Tilt actuator

High Level Functional Decomposition

The "quality" of the images has a logical dependency on:

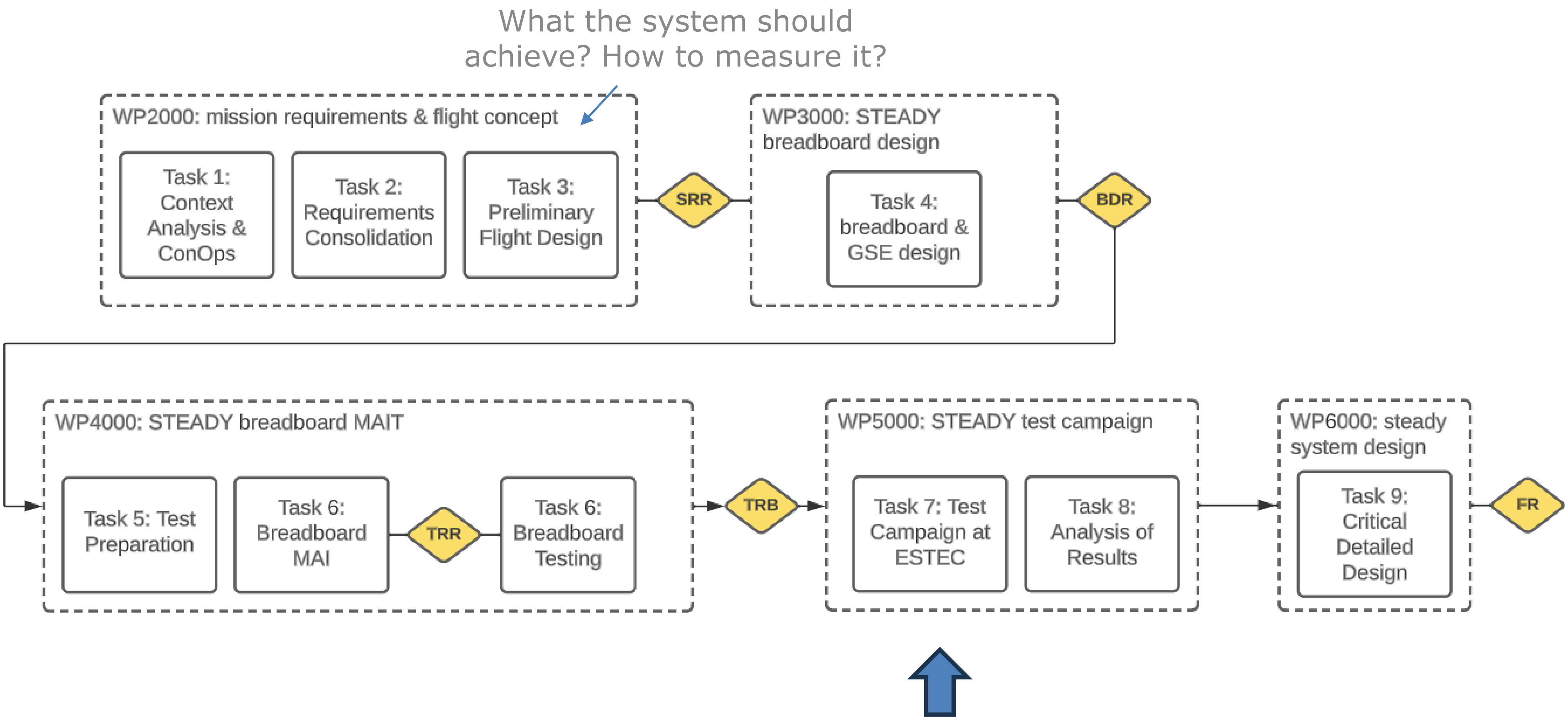
I. Rover Design Characteristics (camera specifications, elasto-mechanical properties, boogie, wheels, suspensions, etc..)
II. Rover Operations (speed, acceleration, slippage, payloads inducing movements as robotic arms, rotating machinery as radars, etc..)
III. Environmental Conditions
    a. Terrain types (smooth, rough, rocky)
    b. Illumination (shadowing, dust, …)
    c. Gravity



Challenges to be addressed

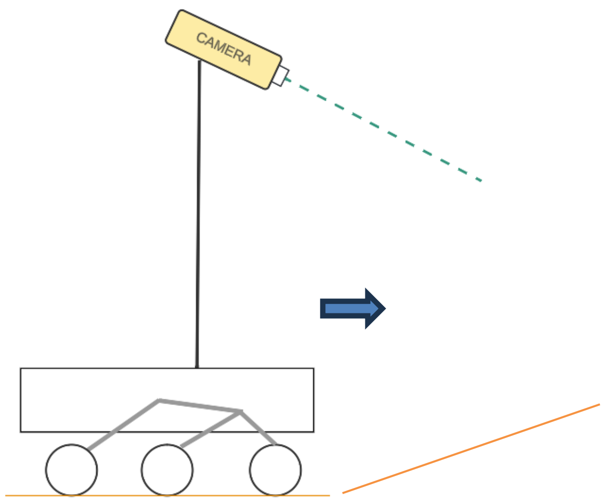
1. How should STEADY behave in terms of ‘line of sight pointing’?
2. What is the typical vibration spectrum or – more generally – the input motion of the interface (intensity, amplitude, …)?
3. What is a ‘good image’? How do we define an *objective* metrics for image classification?
4. How does the ‘camera motion’ influence the quality of the image?
5. How to verify (test) the design solution?

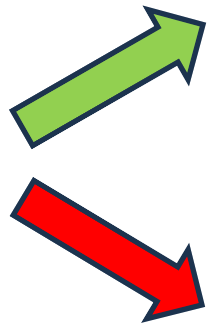
Work Plan


What the system should achieve? How to measure it?
WP2000: mission requirements & flight concept
Task 1: Context Analysis & ConOps
Task 2: Requirements Consolidation
Task 3: Preliminary Flight Design
SRR
WP3000: STEADY breadboard design
Task 4: breadboard & GSE design
BDR
WP4000: STEADY breadboard MAIT
Task 5: Test Preparation
Task 6: Breadboard MAI
TRR
Task 6: Breadboard Testing
TRB
WP5000: STEADY test campaign
Task 7: Test Campaign at ESTEC
Task 8: Analysis of Results
WP6000: steady system design
Task 9: Critical Detailed Design
FR

Understanding De-Pointing Needs

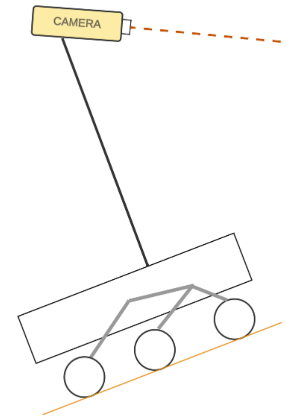
Rover moving towards a slope change:





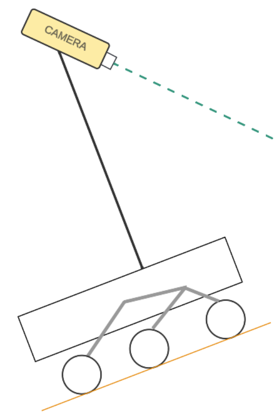
Rover in motion : behavior (1)

'relative' pointing is maintained



Rover in motion : behavior (2)

'absolute' pointing is maintained



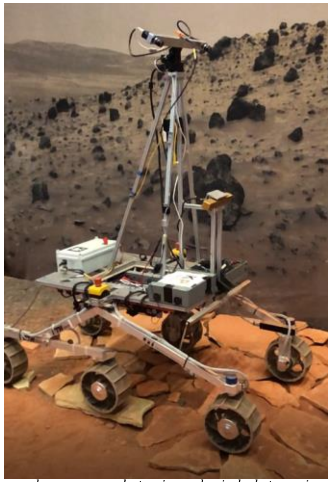
In addition to 'stabilization' needs, STEADY shall enable Camera to follow the (null-motion) body-reference pointing direction

Camera Motion: Reference Use Cases

Two different data sets used for the identification of 'typical' camera I/F motion:

I. Katwijk2015 reference dataset (which has been used to set the frame to the SRR):

II. Dedicated Test Campaign on HDPR

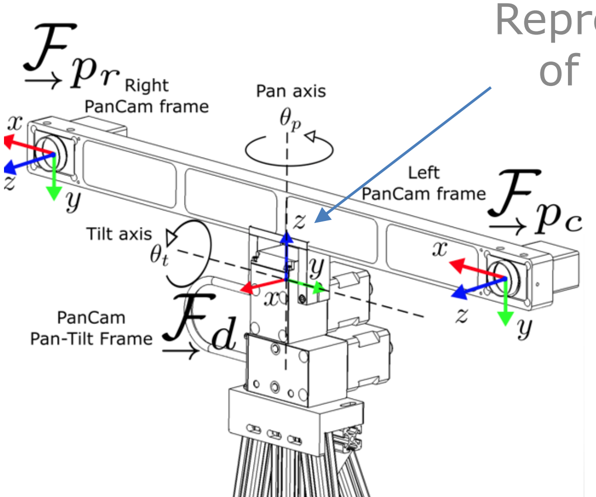


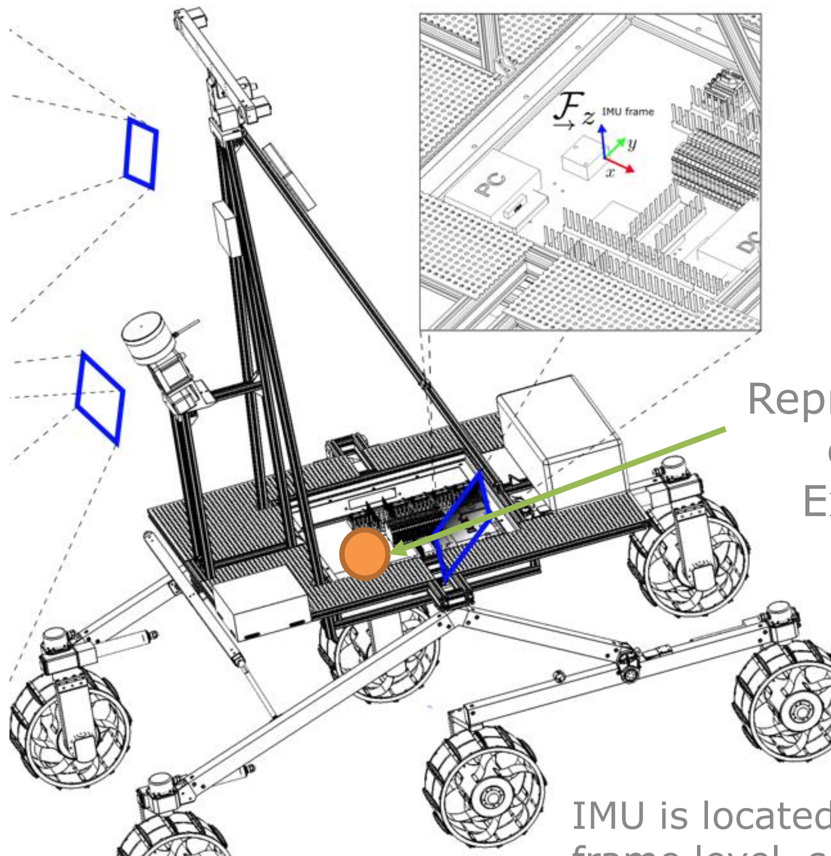
Katwijk 2015 Data Set: Reference Rover Data

- Available Data:
  - Base Vibration Data
  - Design Data

Need :'PanCam Motion' Data

Representative of PanCam



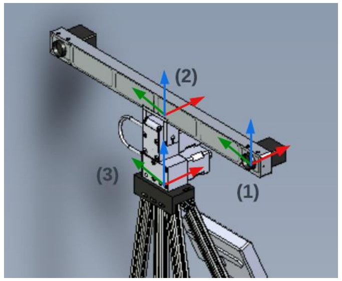


Representative of Base Excitation

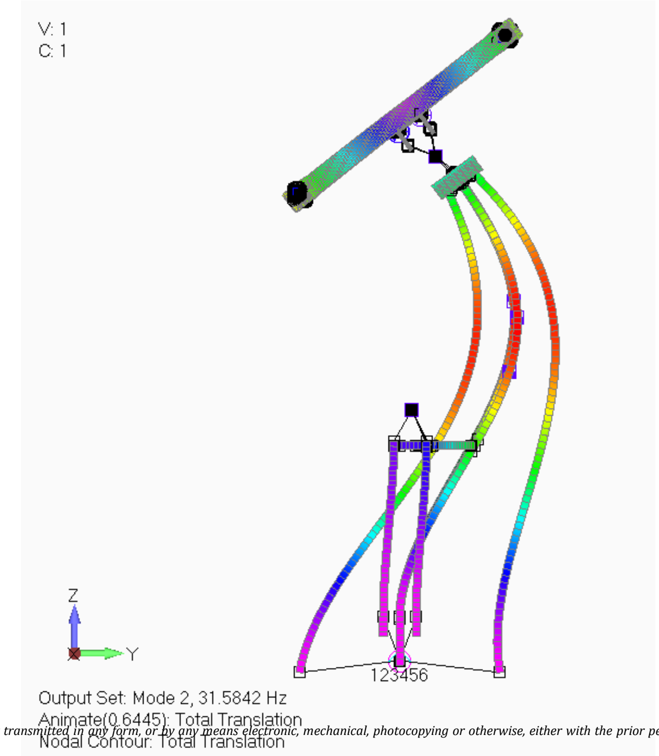
IMU is located at the frame level, so not providing directly the motion of the interface to the camera assembly

Katwijk 2015 Data Set: Reference Rover Data

A model (FEA) based on 'Design Specifications' was built in order to predict the PanCam motion based on available rover data (inertial properties, stiffnesses)



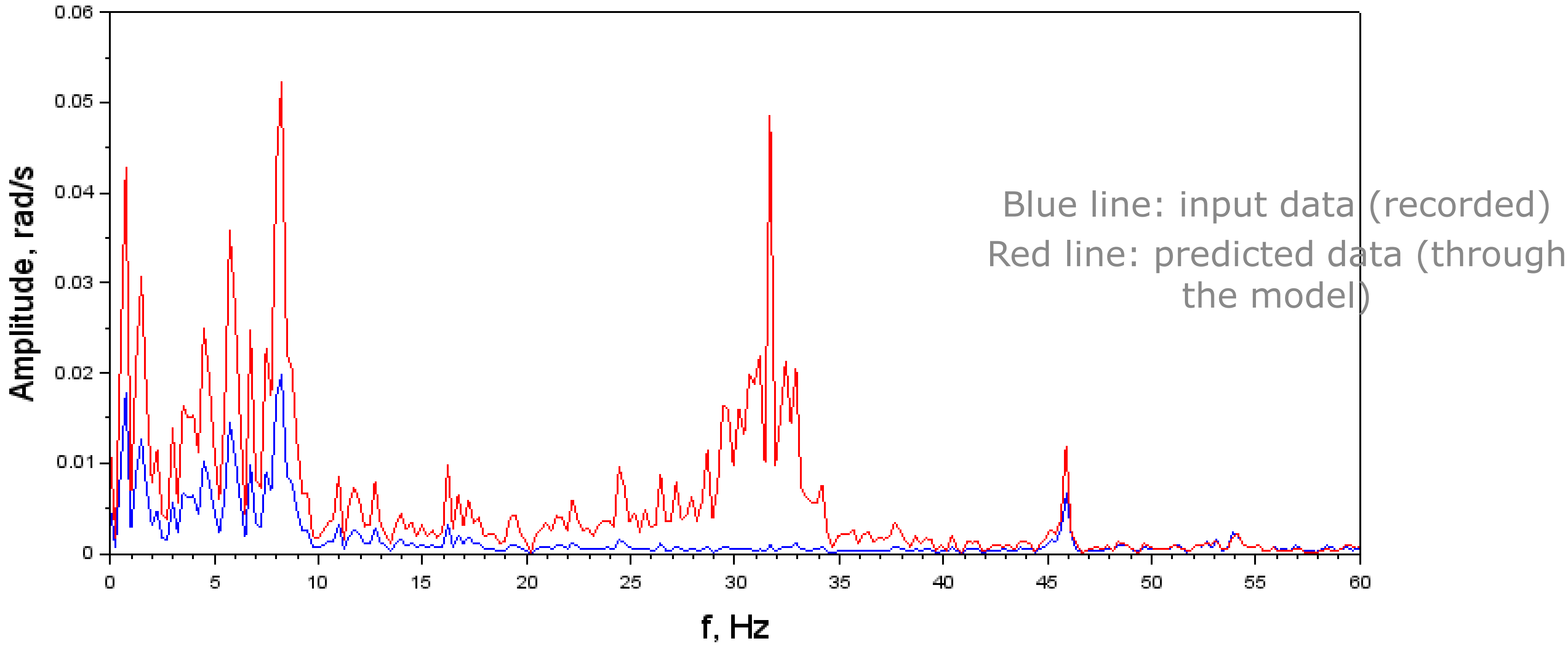
Example of first two modes (18Hz and 31Hz):



Katwijk 2015 Data Set: Reference Rover Data

Finally, a time-history of camera motion could be predicted and used in conjunction with the synchronized time-history of images

Example of prediction of spectral content of camera total angular speed

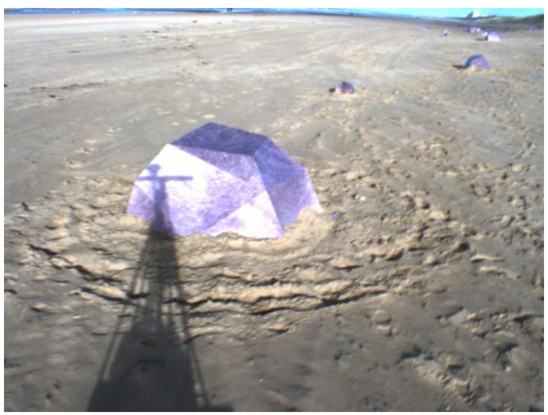


ESTEC Test Campaign (September 2022)

- Scope & purpose:
  - Acquisition of Camera Assembly motion data and Images for different types of terrains and rover speeds (repeatability & control of test cases)
  - Enable comparison with baselined SRR dataset
- HDPR with additional IMU installed
- Test Cases:
  - 3 terrain types (soft, pebbles, tiles)
  - 3 speeds (low, medium, high: 0.1m/s, 0.3m/s, 0.5 m/s)
- Data Processing & Analysis
  - Image Quality (Q-score), off-line post-processing
  - IMU data (base and camera assembly)

Developing a Metrics for Image Quality

- *Objective:* answer the question 'what is the threshold of good image'?
- Proposition: use an algorithm that is sensitive to 'blurriness' and calibrate it via face validation

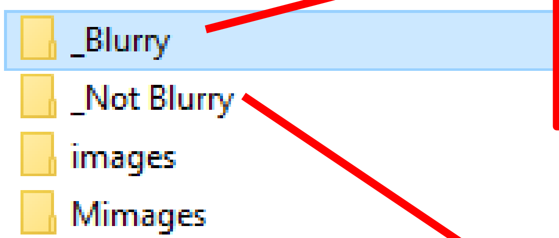


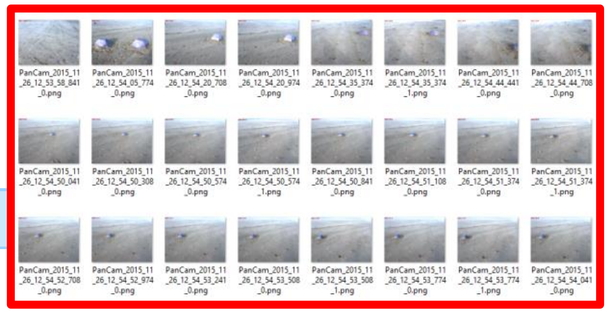
good

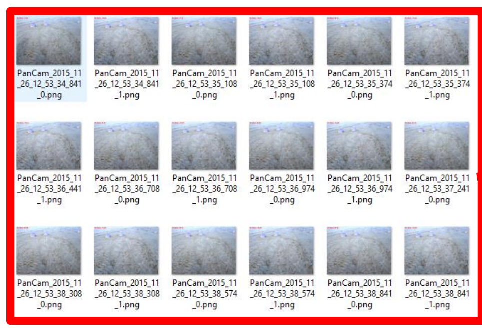
bad

Needs for 'Image-to-Quality' Classifier

Classification of images:
Blurry vs. not-blurry, scoring method proposed







Metrics for Image Quality: the ‘Q-score’

Logic workflow description:

1. Each image of the data set is evaluated with the Classifier: (variance of the Laplacian of the x-y image)
2. A numerical score (real positive number) is assigned to each image - higher numbers indicate higher quality (less blurriness)
3. A normalization is then applied to the calculated value, with respect to nearby image taken when the rover is not moving: this gives the ‘Q-score’

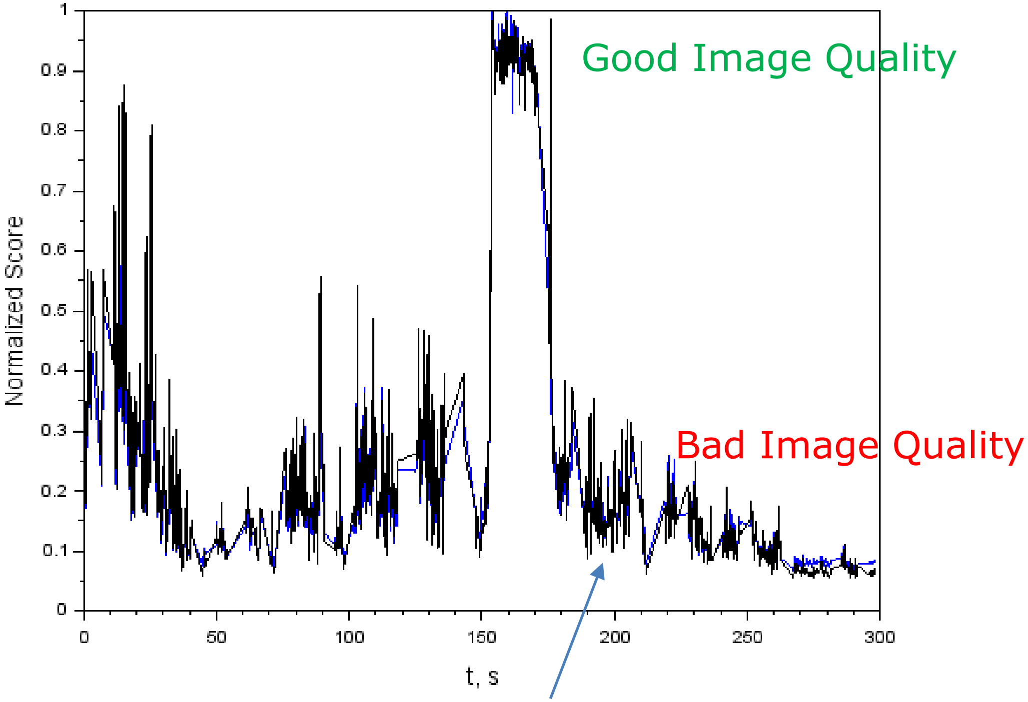
Q-score *judges* the ‘stabilization status’ (not other affecting elements as the camera type, illumination, etc..)

A Q-score higher than **0.30** has been judged acceptable at this stage of development

Reference Data Sets: Analysis

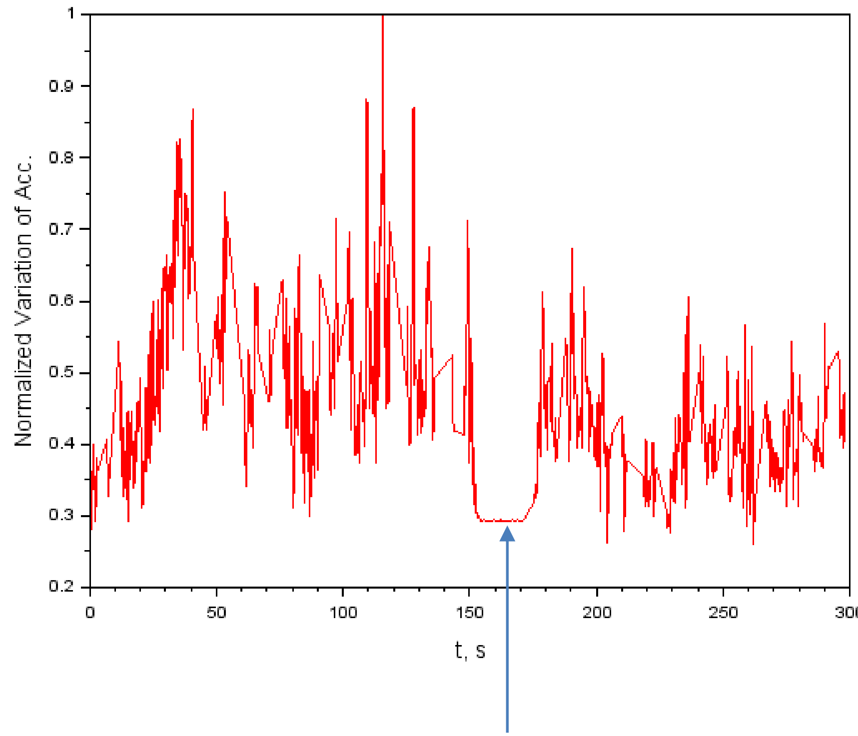
Example: Traverse1_Track4

Normalized Image Score



Blue: ‘L’ camera
Black: ‘R’ camera

Normalized IMU acceleration fluctuation



“Quiet phase”

Relationship btw Image Quality and Motion

- Assumed 'high level' functional relationship:

- Once the functional relationship is established, it would be possible to predict (all other conditions fixed) if the acquisition of an image will be of acceptable quality, given a motion spectrum S_{cam} acting at camera level

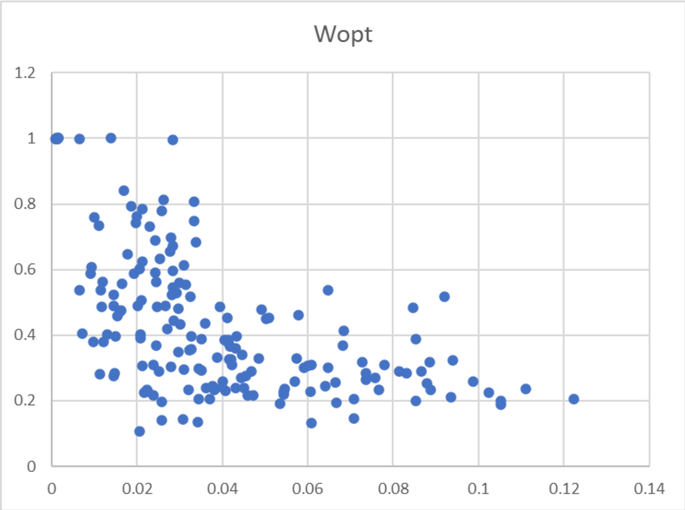
$$Q = Q(S_{Cam})$$

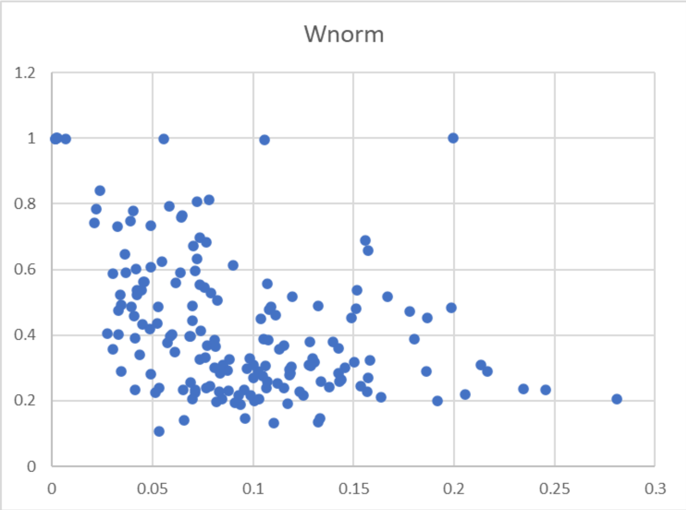
Relationship btw Image Quality and Motion

- Big dataset with quality index, angular speed and velocity components:

Qaverage	QL	QR	Wopt	Wnorm
1	1	1	0.0011	0.0024
0.999056	0.998531	0.999581	0.001352	0.001639
0.999253	0.999799	0.998707	0.006457	0.055449
0.656472	0.651702	0.661242	0.02769	0.157283
0.305678	0.292189	0.319167	0.021251	0.106231
0.451392	0.440541	0.462243	0.041234	0.186461
0.238643	0.217344	0.259942	0.036271	0.115583
0.292349	0.270065	0.314632	0.035188	0.087278
0.318063	0.29912	0.337006	0.072763	0.130509
0.300478	0.273906	0.327049	0.059025	0.080885
0.536676	0.510217	0.563136	0.064809	0.151909
0.387088	0.383019	0.391157	0.03515	0.105387
0.376986	0.360706	0.393266	0.041306	0.057507
0.367019	0.33068	0.403359	0.068277	0.115355
0.243718	0.228491	0.258945	0.064131	0.078394
0.516688	0.506318	0.527059	0.09205	0.166927
0.192406	0.176208	0.208604	0.053502	0.117328
0.326245	0.305574	0.346915	0.041697	0.073493
0.505507	0.468915	0.542099	0.021031	0.082142
0.516762	0.488012	0.545511	0.03258	0.1195
0.30167	0.271342	0.331998	0.064651	0.145627
0.216987	0.195851	0.238123	0.046001	0.124893
0.487015	0.453818	0.520211	0.039506	0.10874
0.228423	0.208347	0.248499	0.054409	0.156732
...	...	...	...	...
...	...	...	...	...

Plots don't provide a quantitative insight





Relationship btw Image Quality and Motion

Data science basic tool comes in handy:

- Covariance Matrix, Pearson correlation (normalized measurement of the covariance)

covariance matrix example

	Qav	QL	QR	Wopt	Wn	WoptMax	WnMAX
Qav	1	1.000	1.000	-0.642	-0.848	-0.671	-0.817
QL	1.000	1	0.999	-0.644	-0.851	-0.675	-0.815
QR	1.000	0.999	1	-0.639	-0.845	-0.667	-0.818
Wopt	-0.642	-0.644	-0.639	1	0.440	0.981	0.378
Wn	-0.848	-0.851	-0.845	0.440	1	0.504	0.896
WoptMax	-0.671	-0.675	-0.667	0.981	0.504	1	0.431
WnMAX	-0.817	-0.815	-0.818	0.378	0.896	0.431	1

Cleaning up

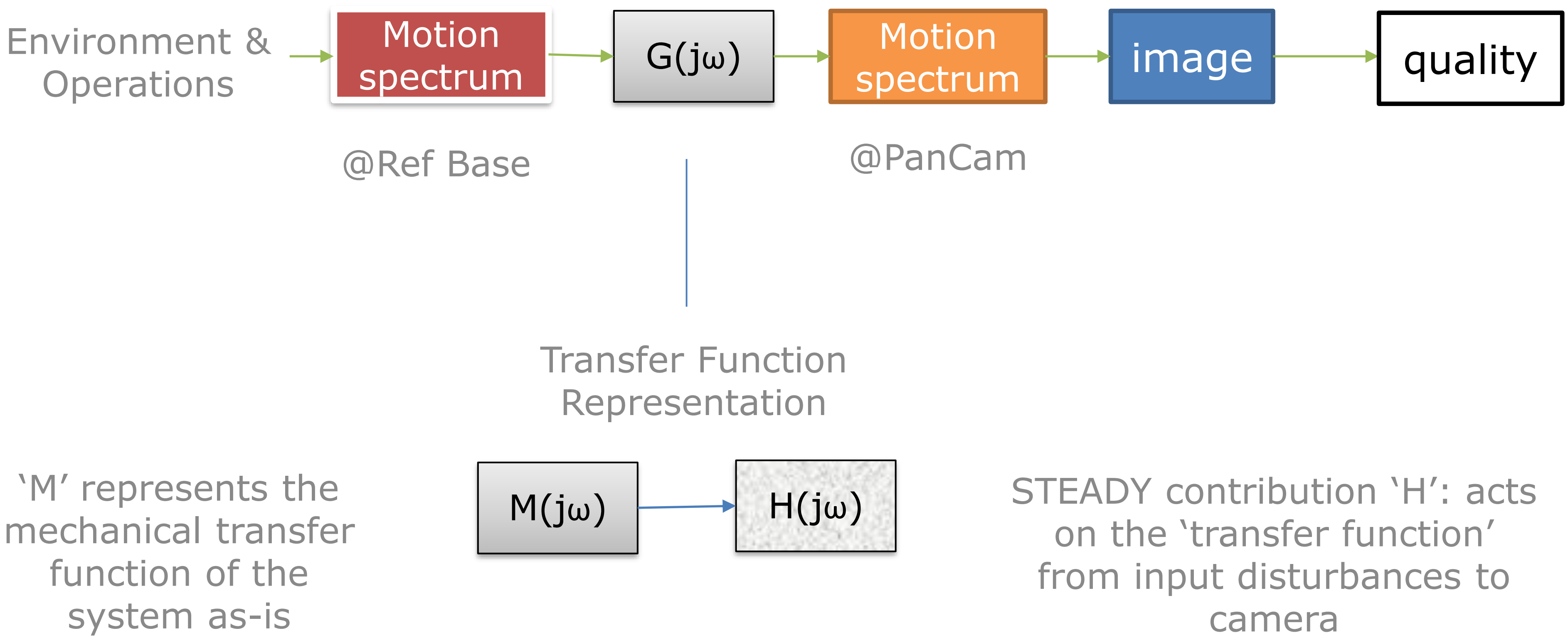
Angular speeds components

				Wopt	Wn	WoptMax	WnMAX
Qav				-0.64193	-0.84805	-0.67099	-0.81661
QL							
QR							
Wopt					0.440175		0.378244
Wn						0.504335	
WoptMax							0.430671
WnMAX							

- Left and right camera data are consistent (strongly positively correlated) – dataset validation
- Angular speed components (normal and optical axis) are strongly negatively correlated with image quality

The threshold of 0.30 for Q-score (requirement) leads to a target time-average (over the acquisition time of the camera) angular speed of **6 deg/s**

Influence Diagram

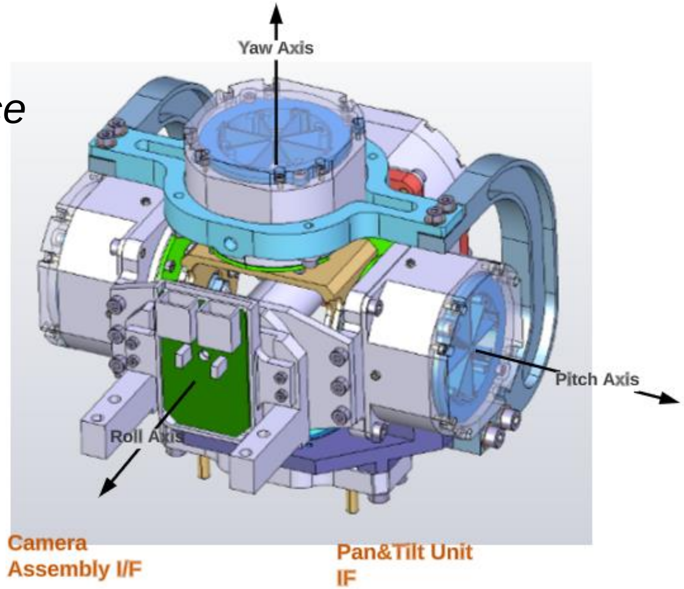


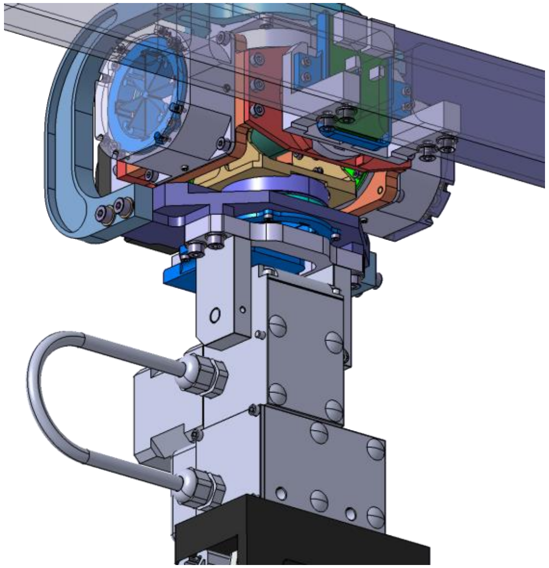
$$Q = Q(H; M, S_{base})$$

Overview

STEADY is conceived as an Image Stabilization device based on a combined active and passive vibration suppression concept:

Device

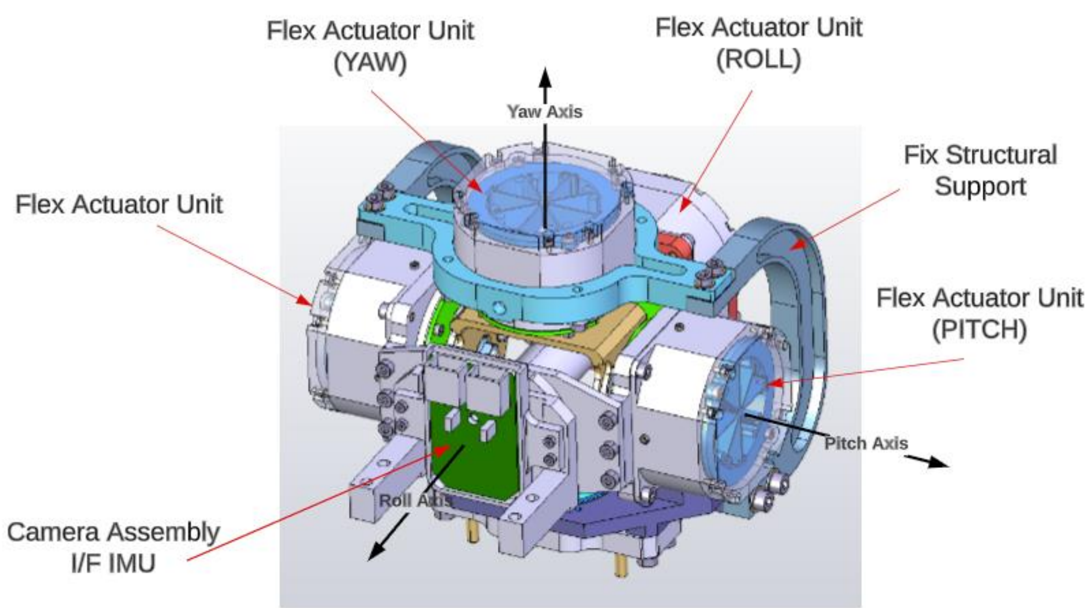




The elasto-mechanical characteristics of STEADY enables partial passive decoupling of the camera assembly of the rover with respect to the rest of the vehicle.

Equipped with Inertial Measurement Units and Limited Angle Torquers, a feedback control law enables to adjust gimbals damping and rotational motion control (0Hz-8Hz bandwidth).

Overview



Operational Modes:

- Mode 0: Monitoring (DEFAULT mode)
- Mode 1: Initialization Mode. Sequence of actuations for visual check of good health electro-mechanical status
- Mode 2: Stabilization Mode

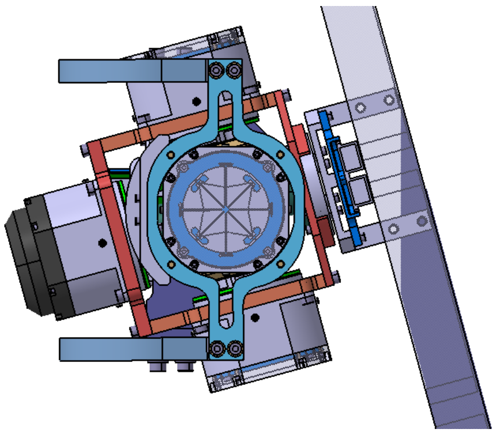
Data storage

Dedicated control unit electronics (CSE)

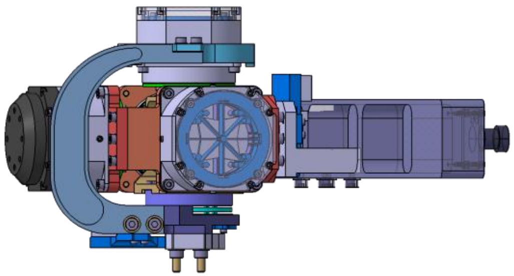
Overview: Kinematics

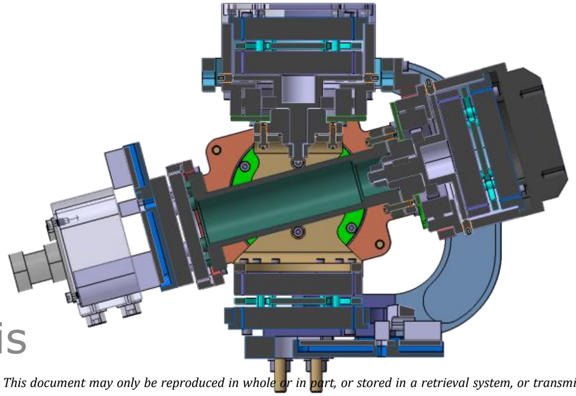
Kinematics: ±15° on each axis

top view: Roll axis



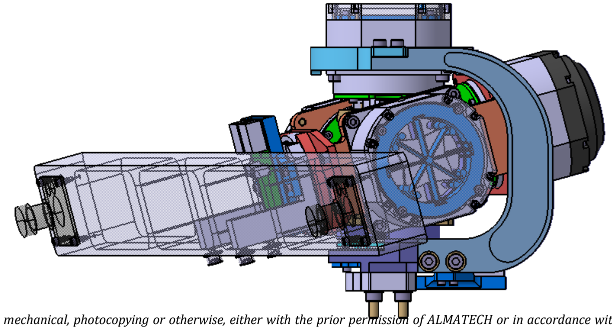
Side view: Yaw axis





Side view (cross section): Pitch axis

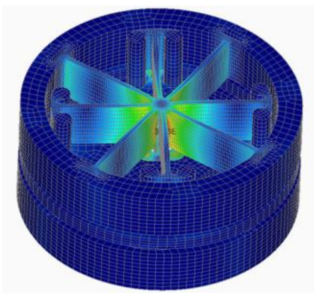
Combined (all axes)



Design Overview: Flex Actuator Unit

Based on the integration of two key sub-elements

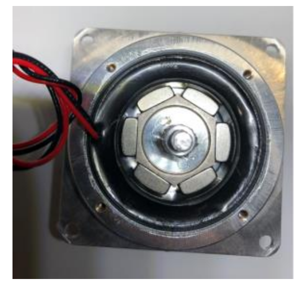
Flexes: Parametrized Design (patented Almatech solution), solutions can be generated with constraint-optimization algorithm



Identifier	Units	Element1-Element2 connection (yaw rotation)	Element2-Element3 connection (pitch rotation)	Element3-Element4 connection (roll rotation)
Peak Radial Force (junction) per FAU	N	**86.7**	**46.1**	**61.5**
Peak Axial Force (junction) per FAU	N	**41.7**	**78.4**	**29.1**

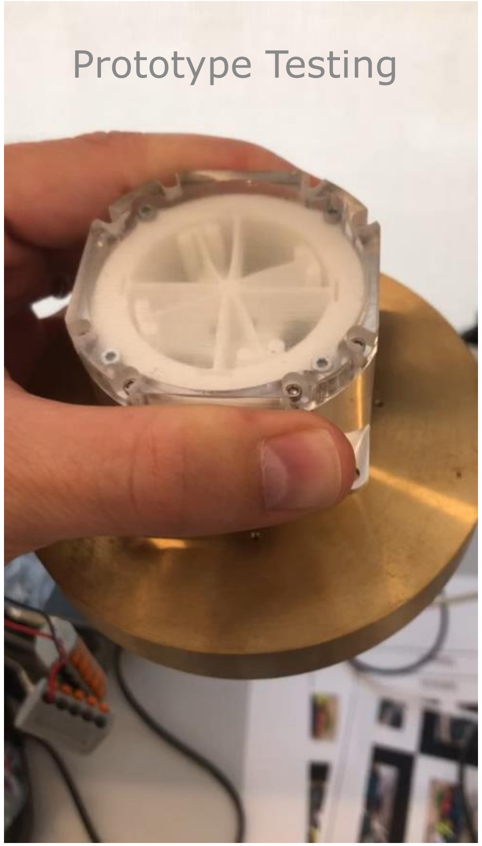
Limited Angle Torquer

("friction-free" solution) – COTS solution for the Proof-Of-Concept



Design Overview: Flex Actuator Unit

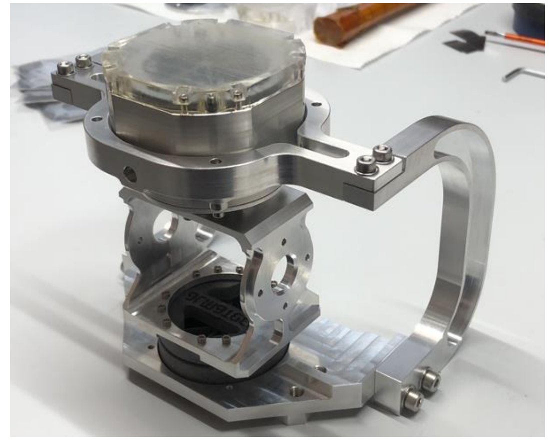
The Flex Actuator Unit (FAU) is an electro-mechanical sub-assembly that provides dynamic decoupling and control capabilities

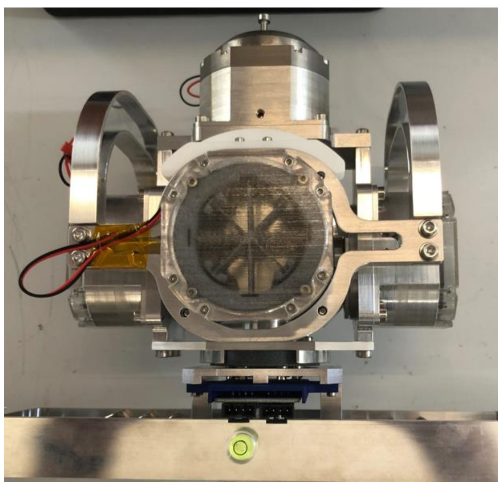


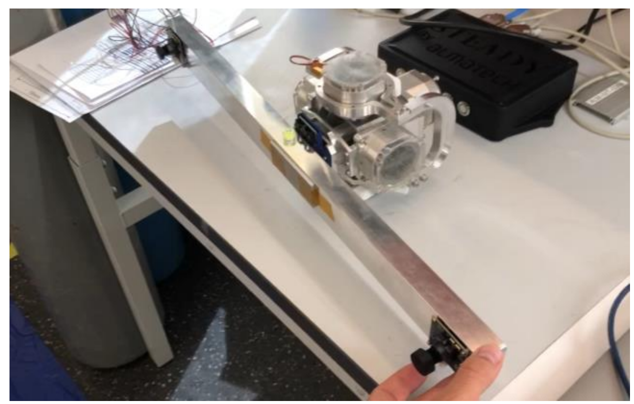
Final Breadboard Manufactured Units

Design Overview: Device Assembly

All three axes are sustained by Flex Actuator Units or simple (passive) flexes







Analyses

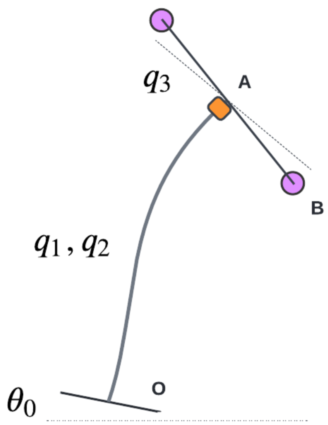
Models developed in support to engineering decision process across the various phases of the design

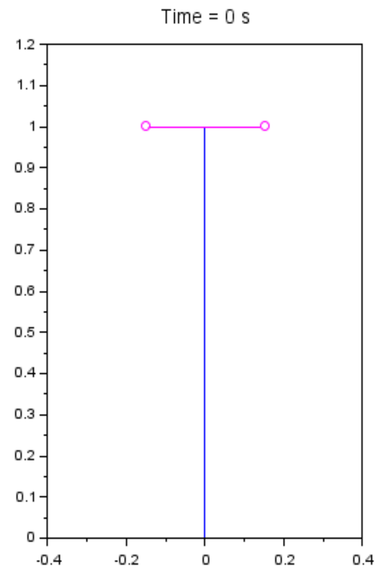
Model Framework:

- Finite Element Analyses (NASTRAN) for testbed structural assessment
- Finite Element Analyses (NASTRAN) for verification of flexes design (different configurations and load cases)
- Reduced Device System model (scilab, ad-hoc algorithm) for the prediction of the coupled Control System and Mechanical behavior of the unit, simulating behavior for different Use Cases (motion of the Pan&Tilt unit interface)
- Monte-Carlo model studies for sensitivity assessment (uncertainty in model parameters and on external inputs)

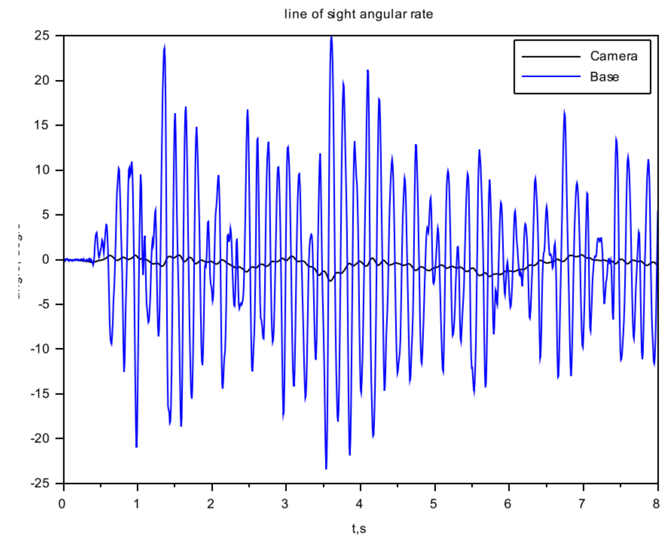
Analyses

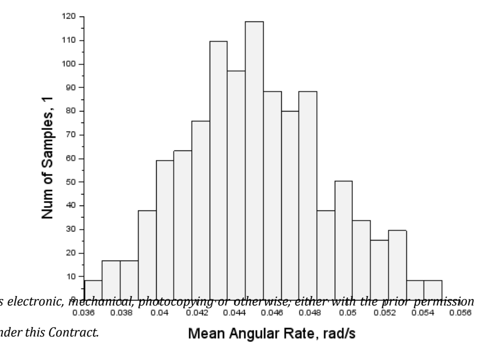
Understanding of how linear accelerations and angular acceleration are transmitted at camera level ('M(jω)')





Predicting Performance of the Device (controlled)





Key Design Drivers

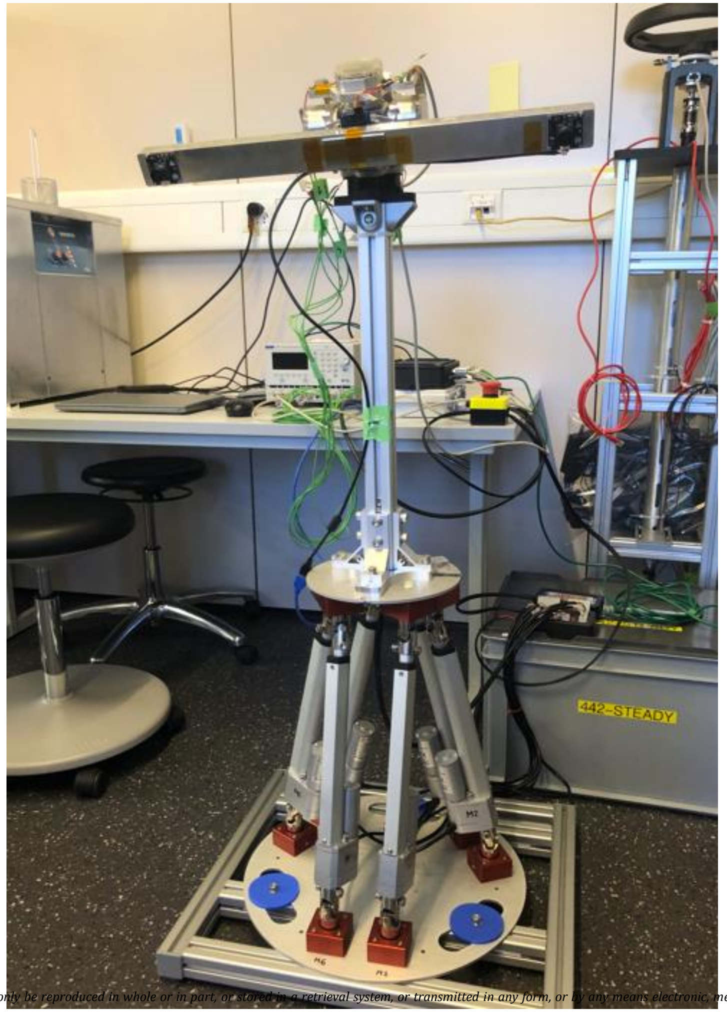
1. Inertial Properties of the camera assembly (mass, CoM location)

2. Interface (input) motion spectrum
   - performance
   - structural integrity

3. Image quality target

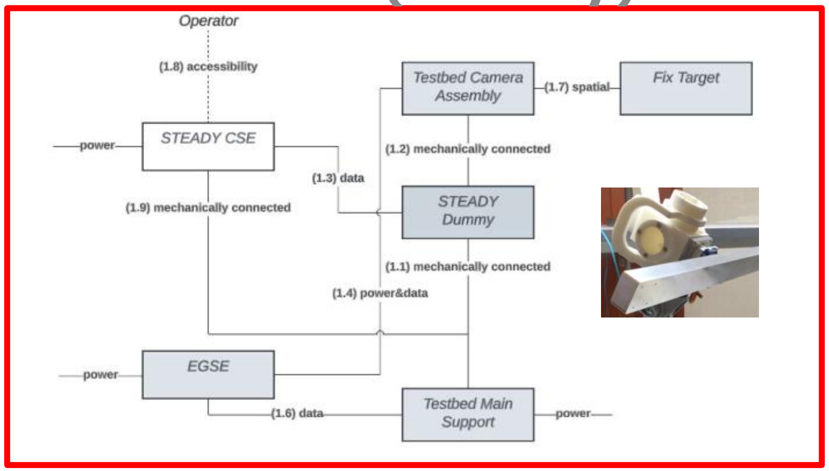
4. Allocated engineering budgets: envelope volume, mass, power

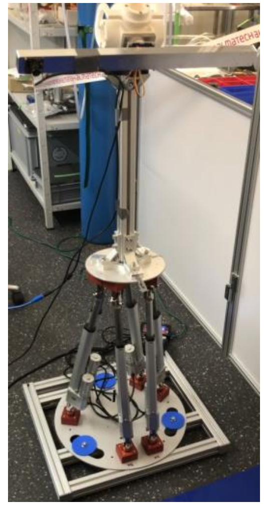
Testing Strategy (at Almatech)



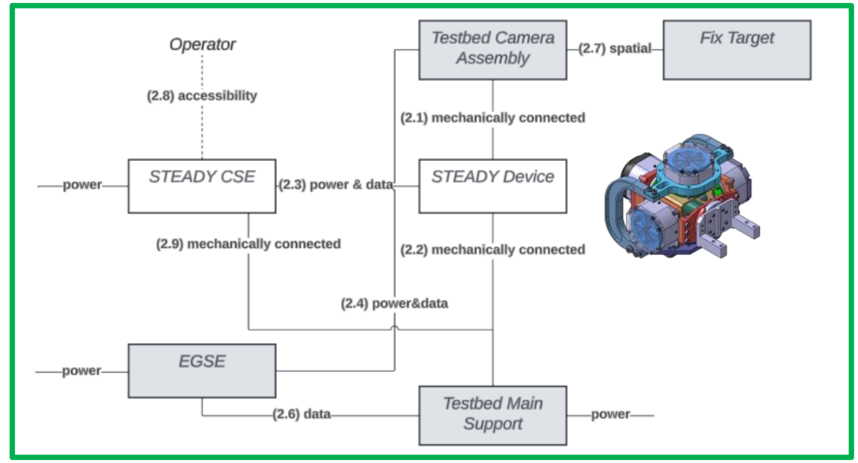
Test Configurations

Conf. 1 (Dummy)





Conf. 2 (Device)



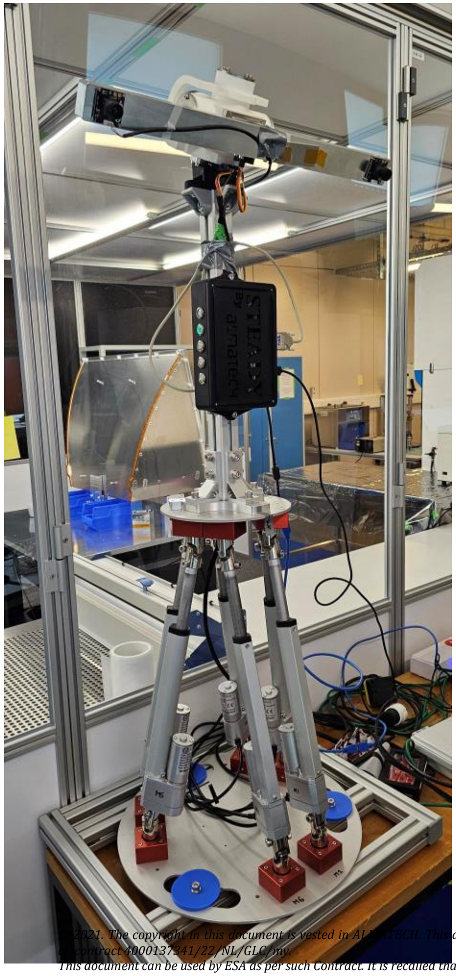
Verification & Validation Activities Phase			
Name	**Hardware Configuration**	**Operational Mode**	**Location / Facilities**
Experiment Sequence A	(Conf. 1) Testbed, with STEADY Dummy	Mode 0.1 – Monitoring & Data Logging	Almatech workshop
Experiment Sequence B	(Conf.2) Testbed with STEADY device	Mode 0.1 – Monitoring & Data Logging	Almatech workshop
Experiment Sequence C	(Conf. 2) Testbed with STEADY device	Mode 1.1 - Initialization Mode and Data Storage, Mode 2.1 - Stabilization	Almatech workshop

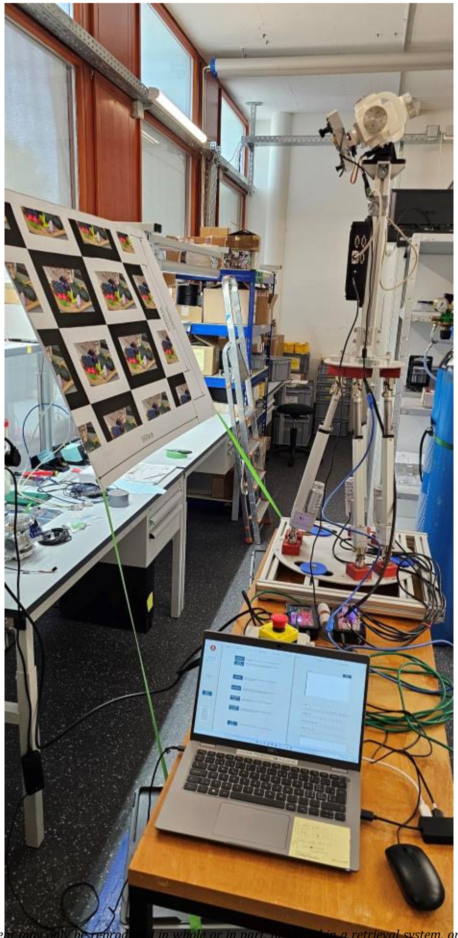
Operational Modes:

- **Mode 0:** Monitoring (DEFAULT mode)
    - **Mode 0.1:** Monitoring and Data Storage:
- **Mode 1:** Initialization Mode. Sequence of actuations
    - **Mode 1.1:** Initialization Mode and Data Storage:
- **Mode 2:** Stabilization Mode.
    - **Mode 2.1:** Stabilization Mode and Data Storage

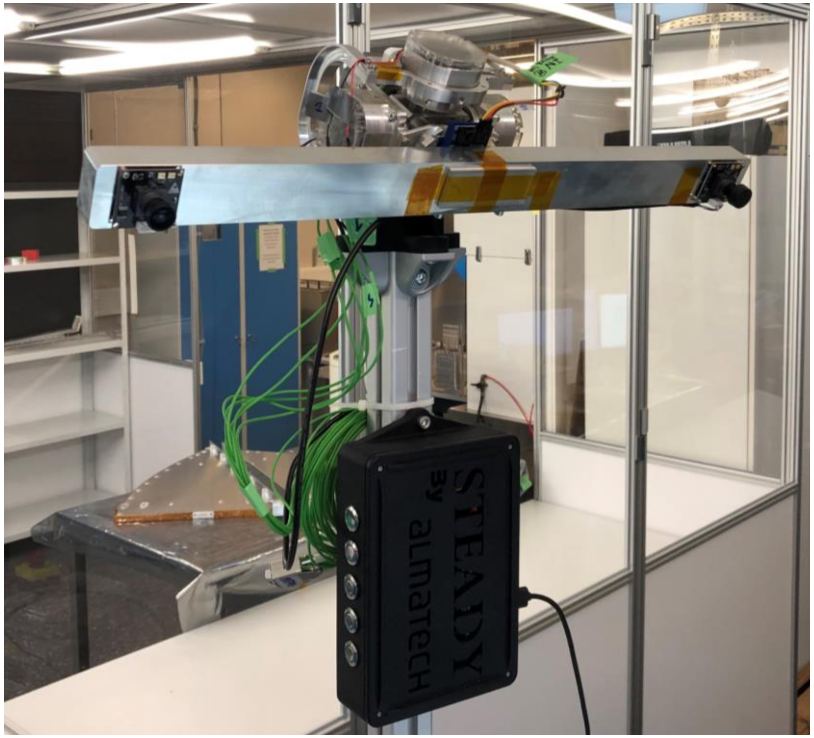
Test Configurations

Conf. 1 (Dummy)



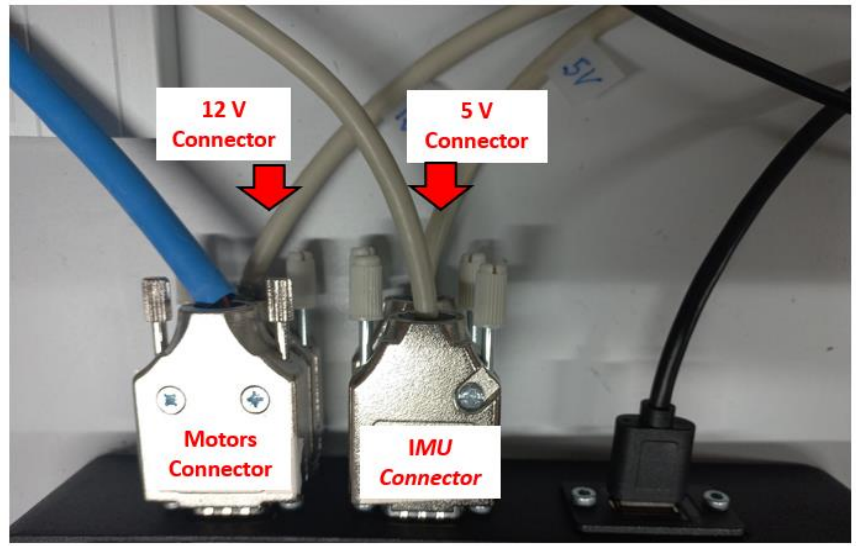


Conf. 2 (Device)



Test Configurations

Control System Electronics (CSE)



Mode 2.1: Stabilization Mode and Data Storage

Test Cases (TC) & Use Cases (UC)

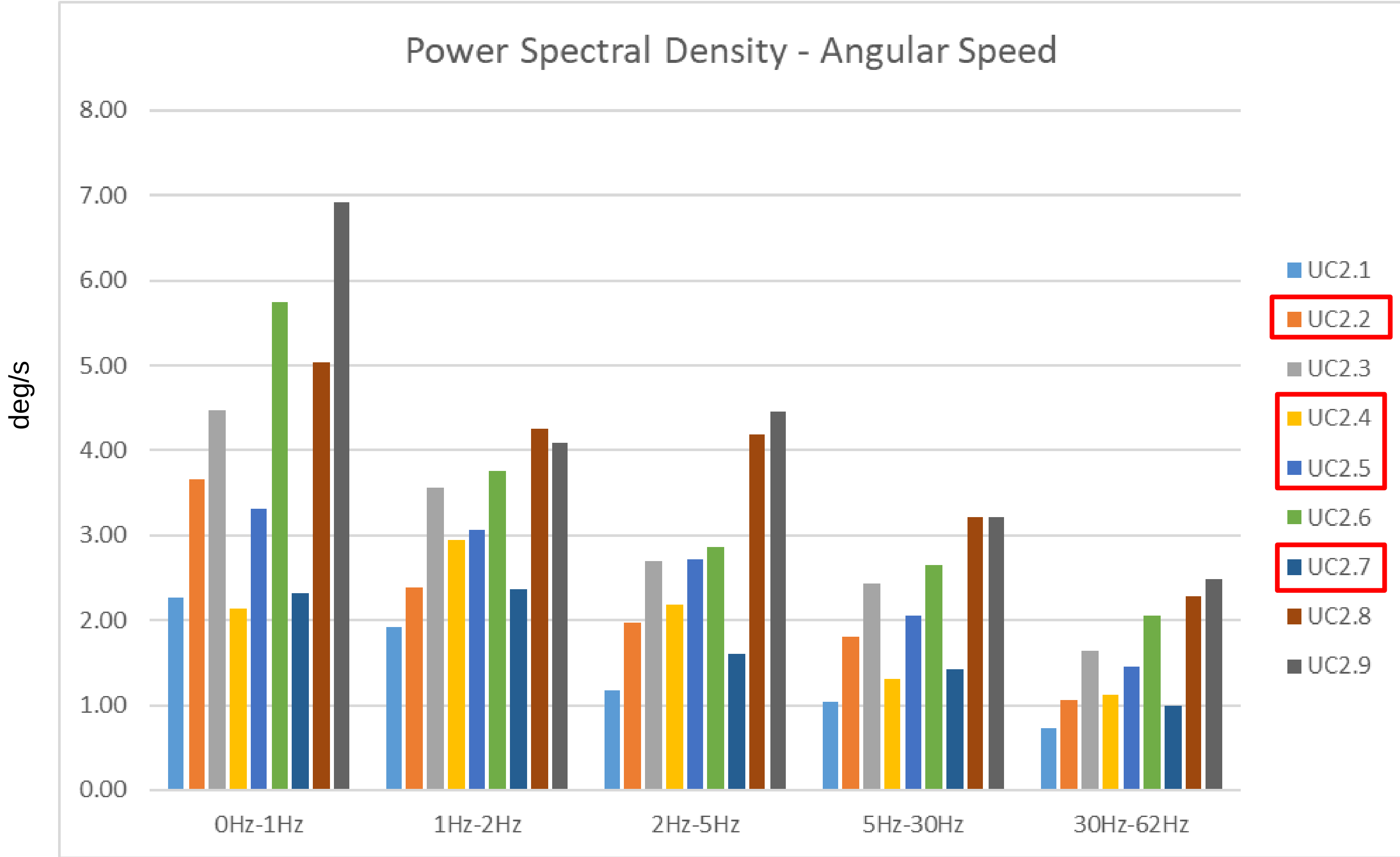
Use Cases (Katwijk 2015 and ESTEC 2022)								
Campaign	ID	Ref.	Average Power Index	Peak Power Index	Mean Omega	Max Omega	Feasible for BBM	Test Case for BBM
			W/kg	W/kg	rad/s	rad/s	-	-
Katwijk 2015	**UC1.12**		0.0551	0.1902	0.0311	0.0741	x	
ESTEC 2022	**UC2.1**	Run1	0.0280	0.2049	0.0294	0.0988	x	
Katwijk 2015	**UC1.14**		0.0660	0.4161	0.0569	0.1228	x	
ESTEC 2022	**UC2.4**	Run4	0.0377	0.3703	0.0307	0.1464	x	TC10
ESTEC 2022	**UC2.7**	Run7	0.0897	0.7825	0.0432	0.1658	x	TC11
Katwijk 2015	**UC1.13**		0.1668	0.9627	0.0606	0.1699	x	
ESTEC 2022	**UC2.2**	Run2	0.3346	2.6130	0.0909	0.2407	x	TC12
Katwijk 2015	**UC1.15**		0.4165	2.7631	0.0762	0.2426	x	
ESTEC 2022	**UC2.5**	Run5	0.2497	1.7619	0.1056	0.3100	x	TC13
Katwijk 2015	**UC1.7**		0.3477	1.7427	0.1121	0.3146	x	
Katwijk 2015	**UC1.8**		0.1801	1.7411	0.0895	0.3772	x	
ESTEC 2022	**UC2.8**	Run8	0.8983	5.6163	0.1604	0.4472		
ESTEC 2022	**UC2.10**	Run10	0.5003	2.9987	0.1289	0.4543		
ESTEC 2022	**UC2.3**	Run3	0.6038	6.1223	0.1409	0.4595		
ESTEC 2022	**UC2.6**	Run6	0.5985	5.7165	0.1515	0.4949		
ESTEC 2022	**UC2.9**	Run9	2.4077	21.2288	0.2788	0.7818		

TC: as executed on testbed
UC: as recorded on HDPR

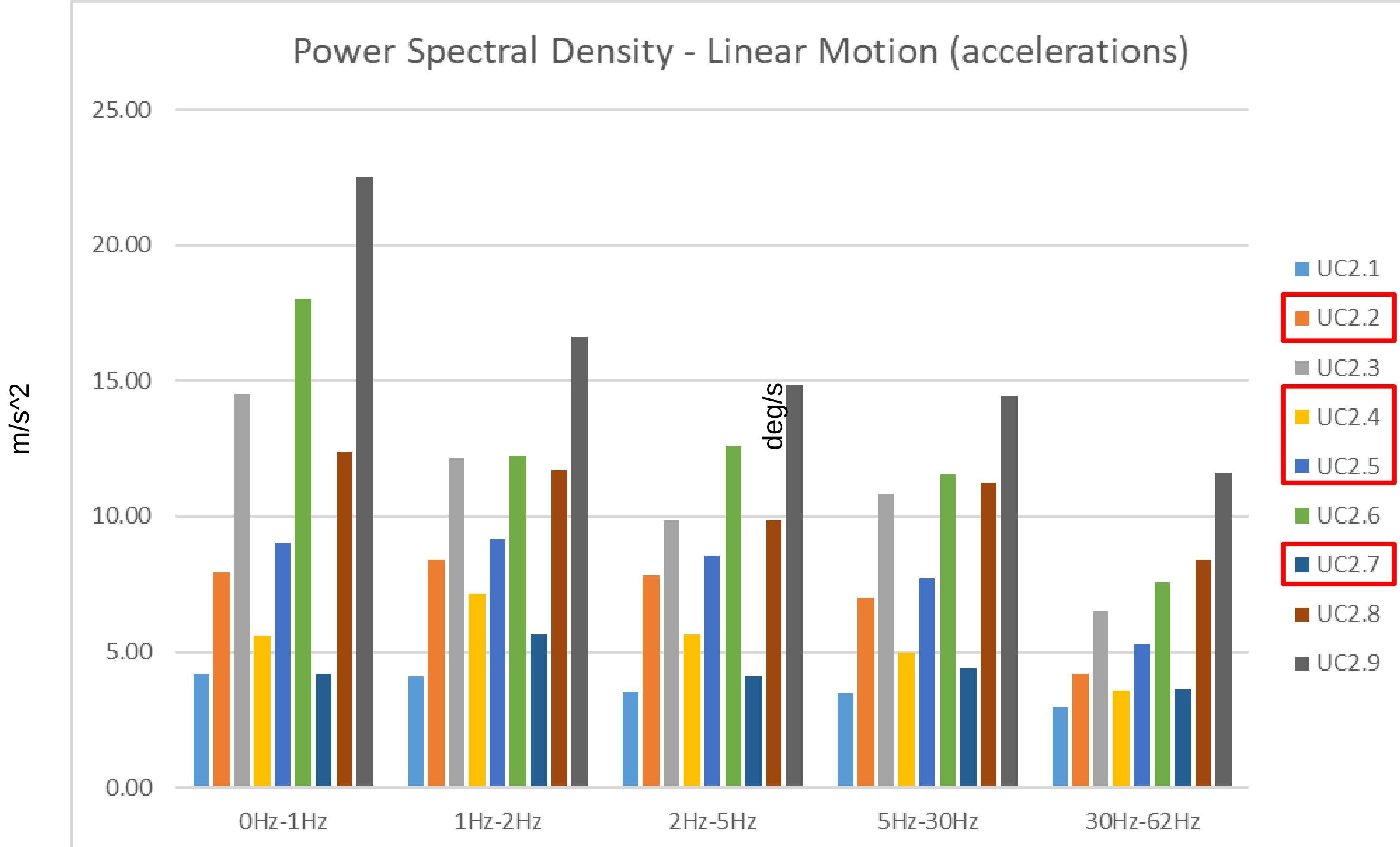
Additionally, 3 reference (benchmark) test cases:

- ROLL sine sweep
- PITCH sine sweep
- YAW sine sweep

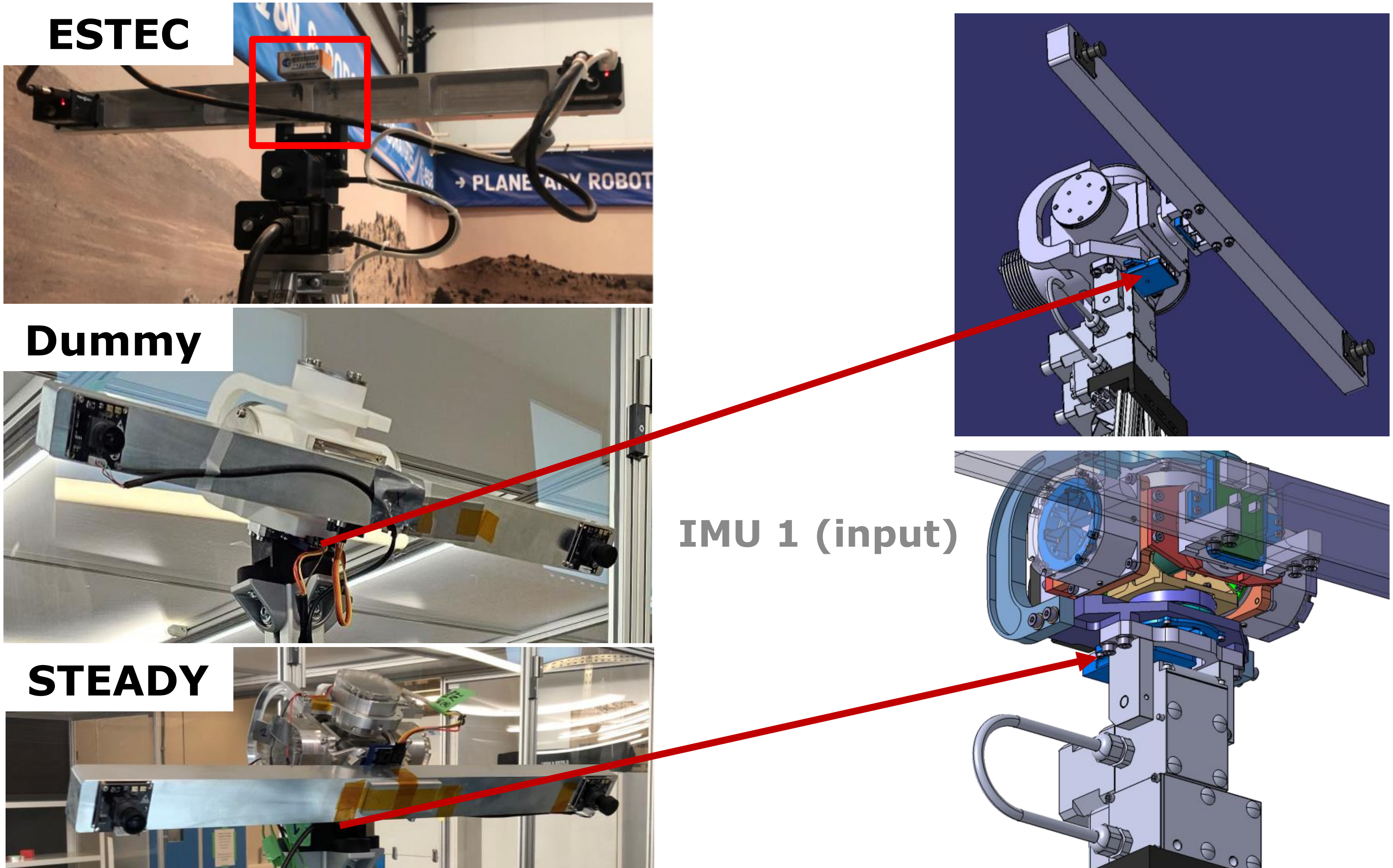
Use Cases – Power Spectral Density



Use Cases – Power Spectral Density

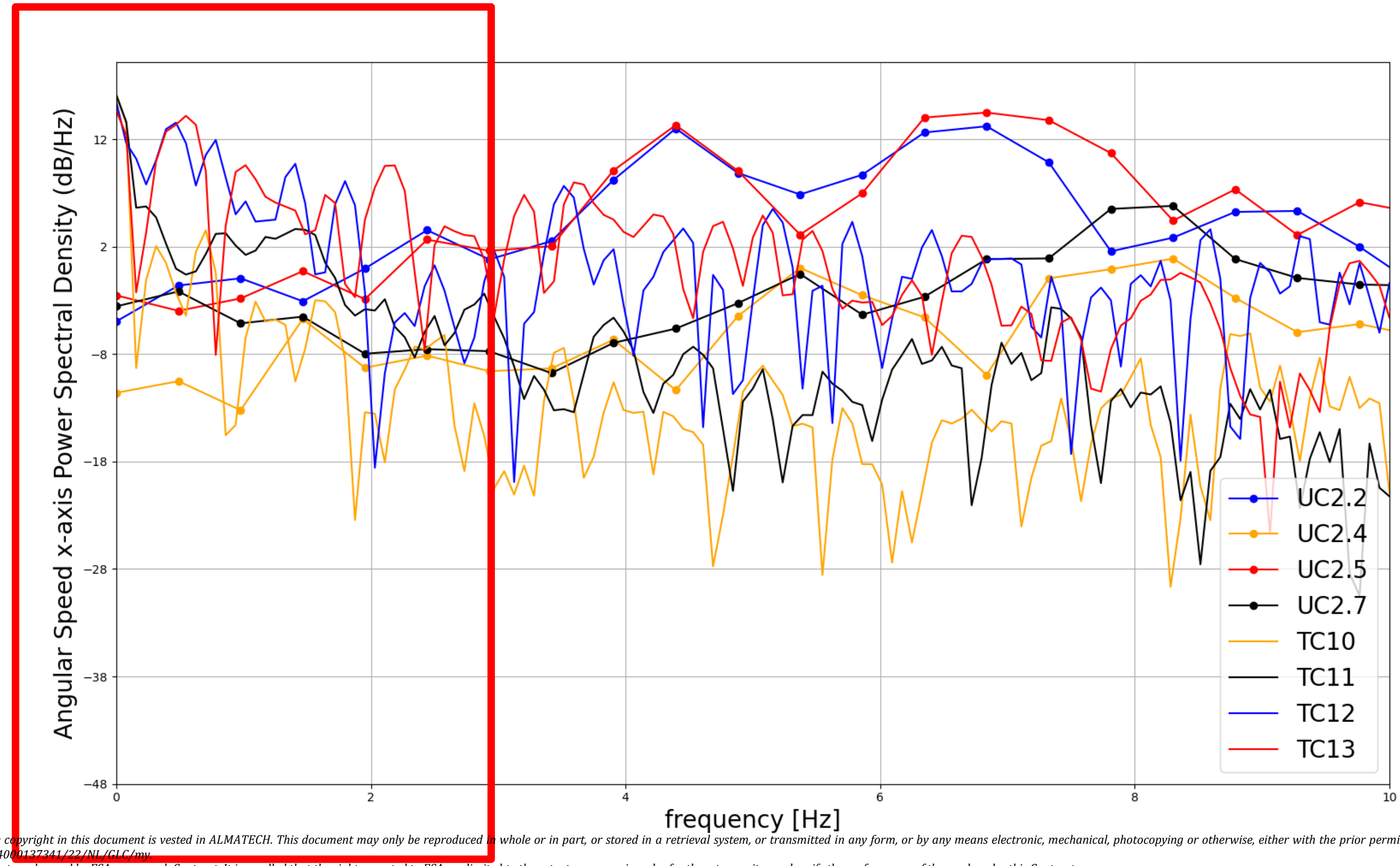


Test Cases & Use Cases Measurement Location



Analysis of Results: UC vs TC Power Spectral Density

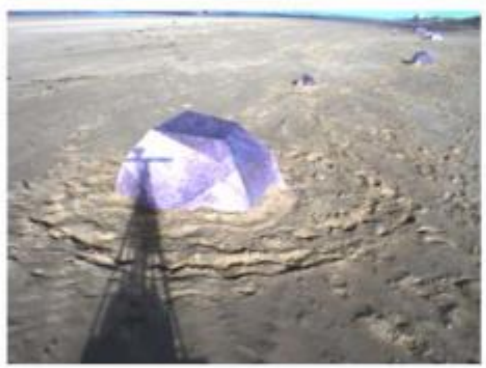
Angular Speed Power Spectral Density comparison between UC and TC IMU1 (input) data



Analysis of Results: Q-Score Algorithm

$$\nabla^2 f = \frac{\delta^2 f}{\delta x^2} + \frac{\delta^2 f}{\delta y^2}$$

Laplace 3x3 convolution matrix

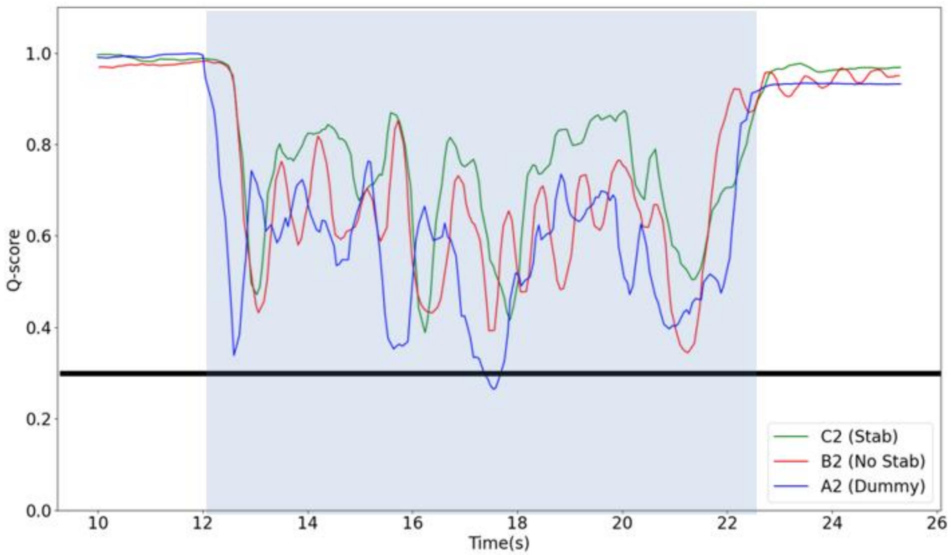


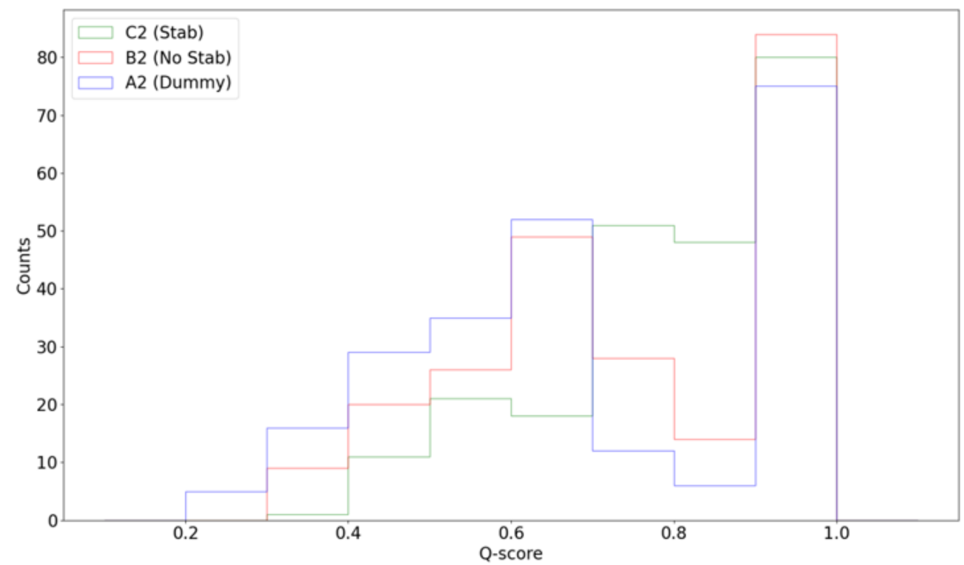
→ Gray Image $* \begin{bmatrix} 0 & 1 & 0 \\ 1 & -4 & 1 \\ 0 & 1 & 0 \end{bmatrix}$ → Variance → Image Quality Score Value

The result of the Laplacian method gives us a single floating-point value for each image which can be used as image quality score value. If the variance falls below a predefined threshold, we can classify the image as a “blurry” image.

Analysis of Results: T10 comparison

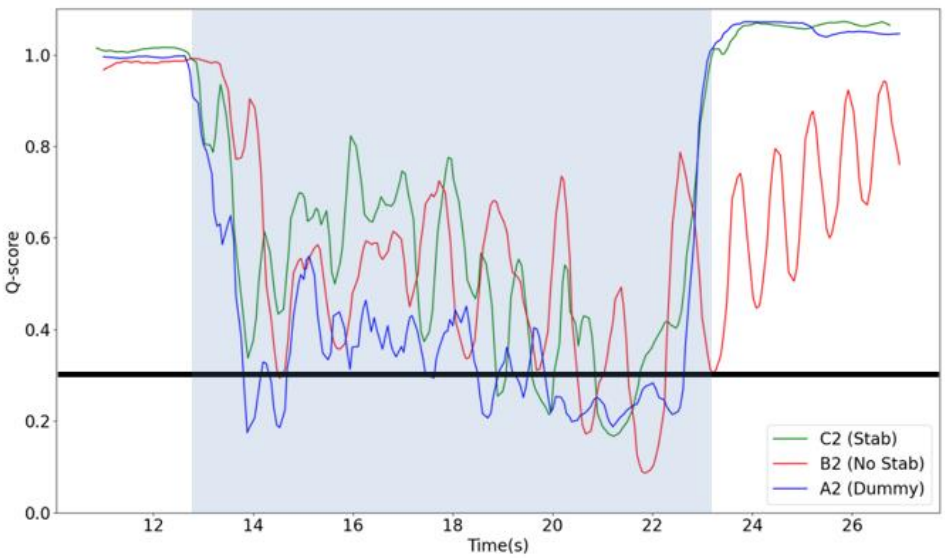
A vs B vs C (Q-score, **T10** Trajectory file) & Q-scores histogram distributions

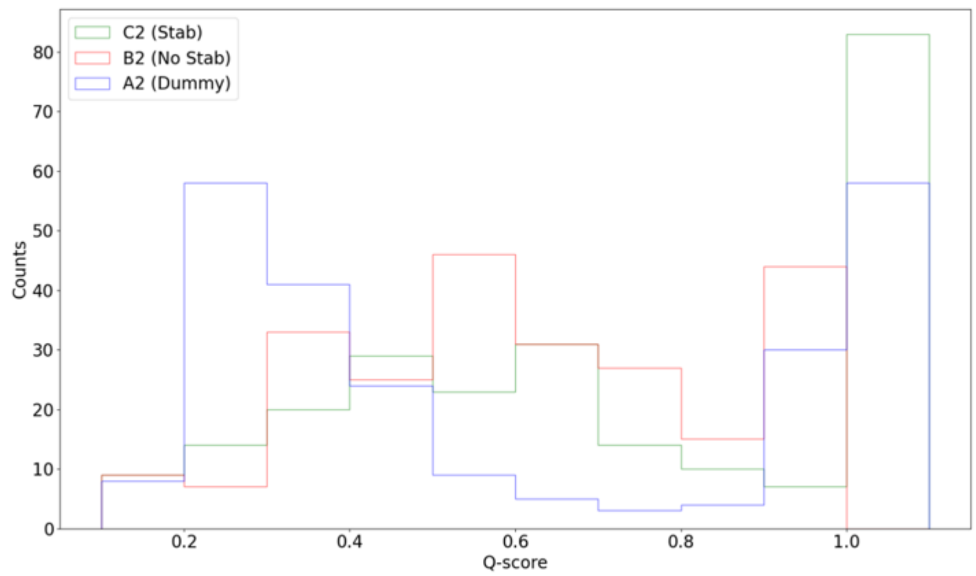




Analysis of Results: T11 comparison

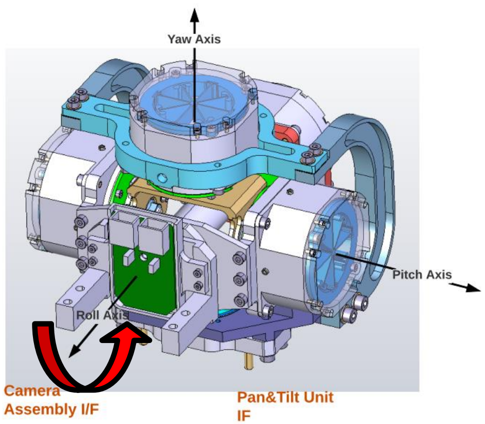
A vs B vs C (Q-score, **T11** Trajectory file) & Q-scores histogram distributions

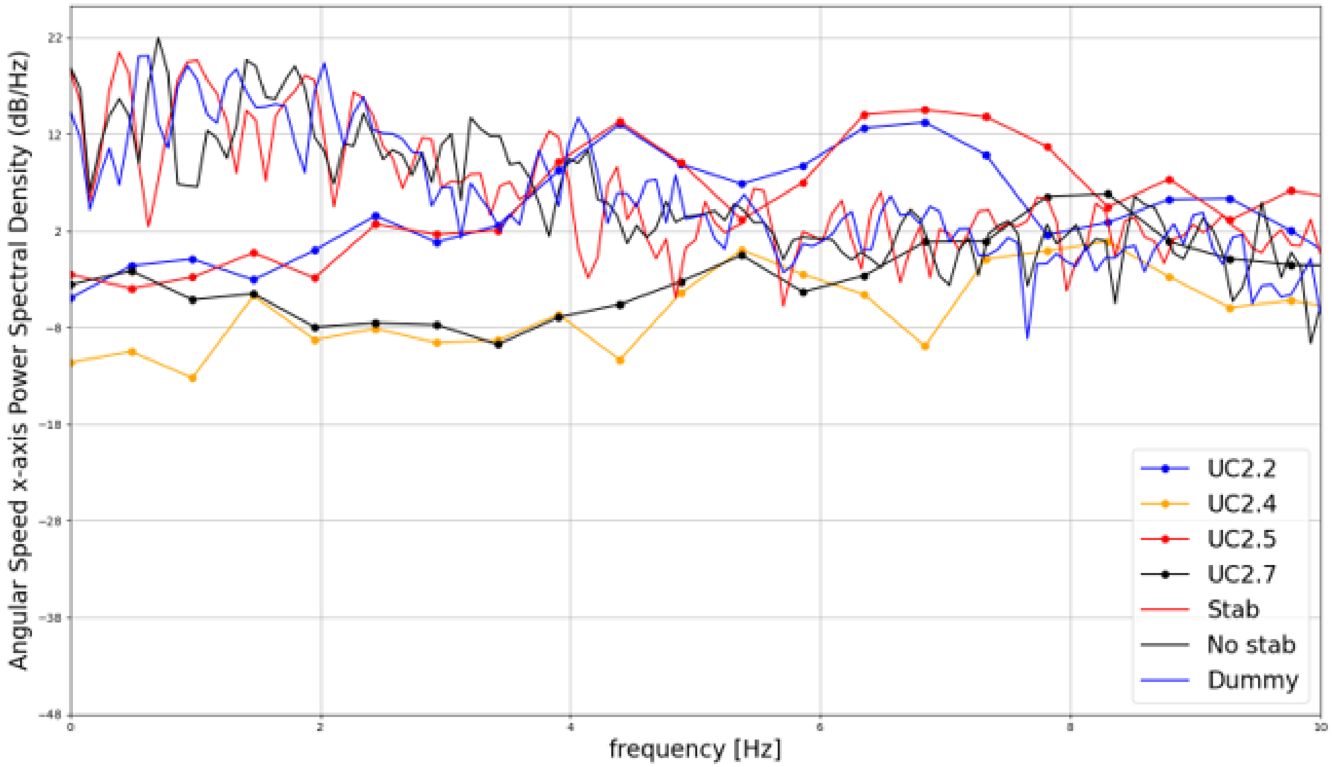




Analysis of Results: UC vs TC Power Spectral Density

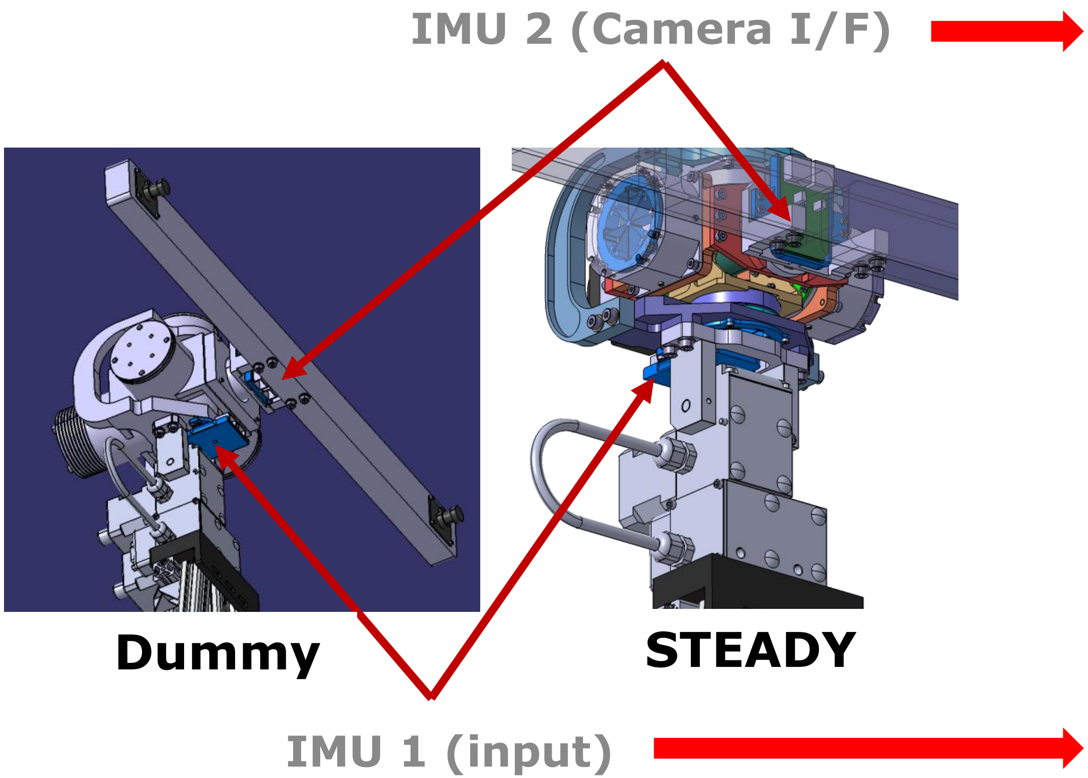
Angular Speed Power Spectral Density comparison between UC and IMU1 (input) Roll Sweep data

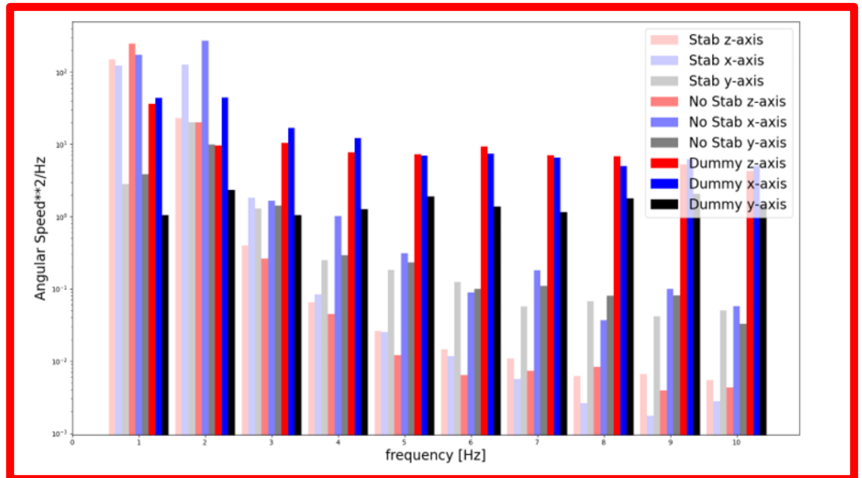


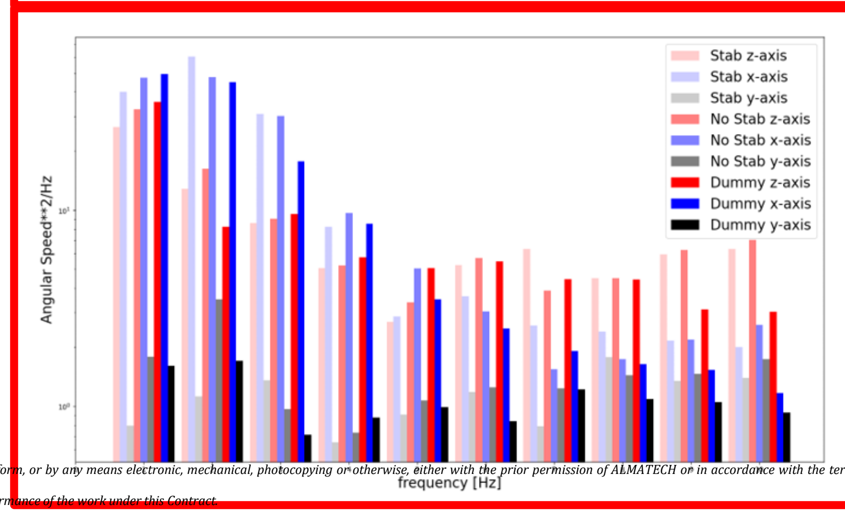


Analysis of Results: Motion Power Spectral Density

ROLL sine sweep Averaged Angular Speed Power Spectral Density comparison.

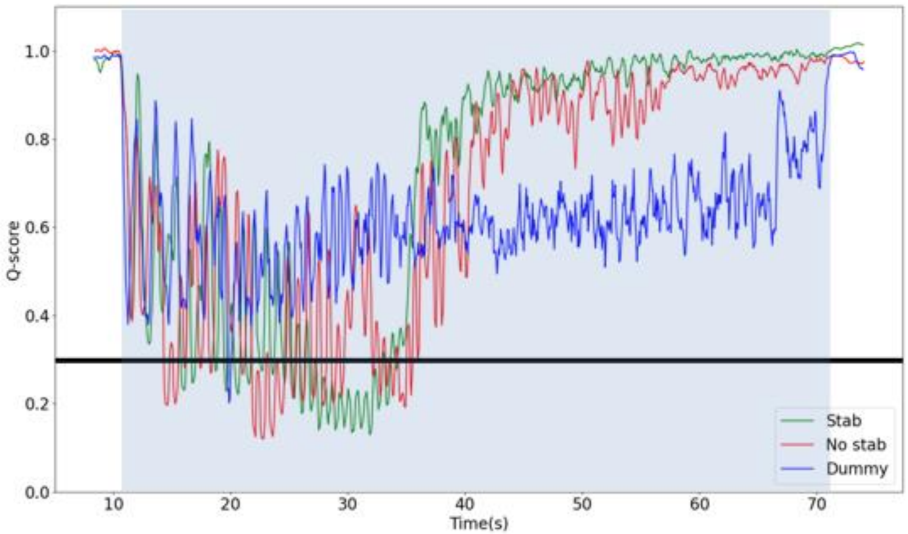


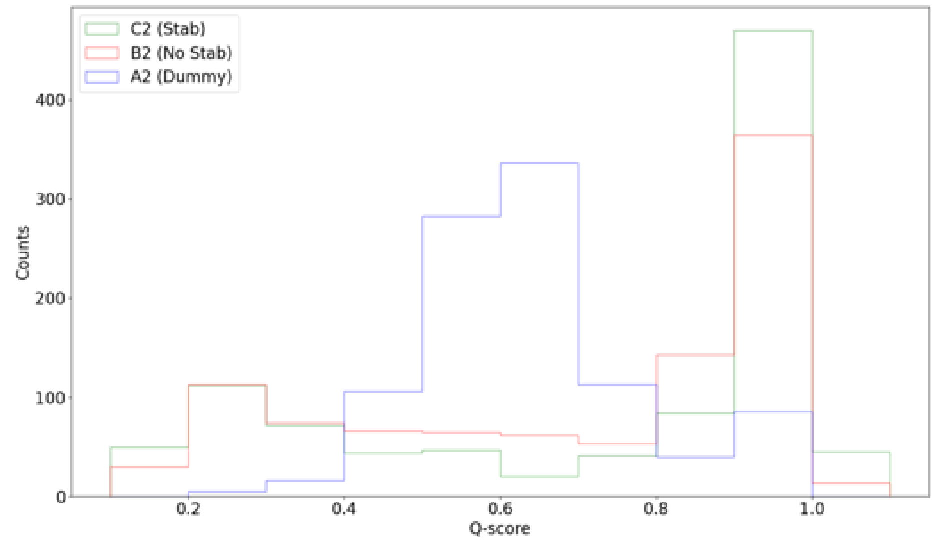




Analysis of Results: ROLL sweep comparison

A vs B vs C (Q-score, **ROLL** sine sweep) & Q-scores histogram distributions





Analysis of Results: Q-score ROLL sweep

Image quality (Q-score) vs. input disturbance frequency for ROLL sine Sweep test case

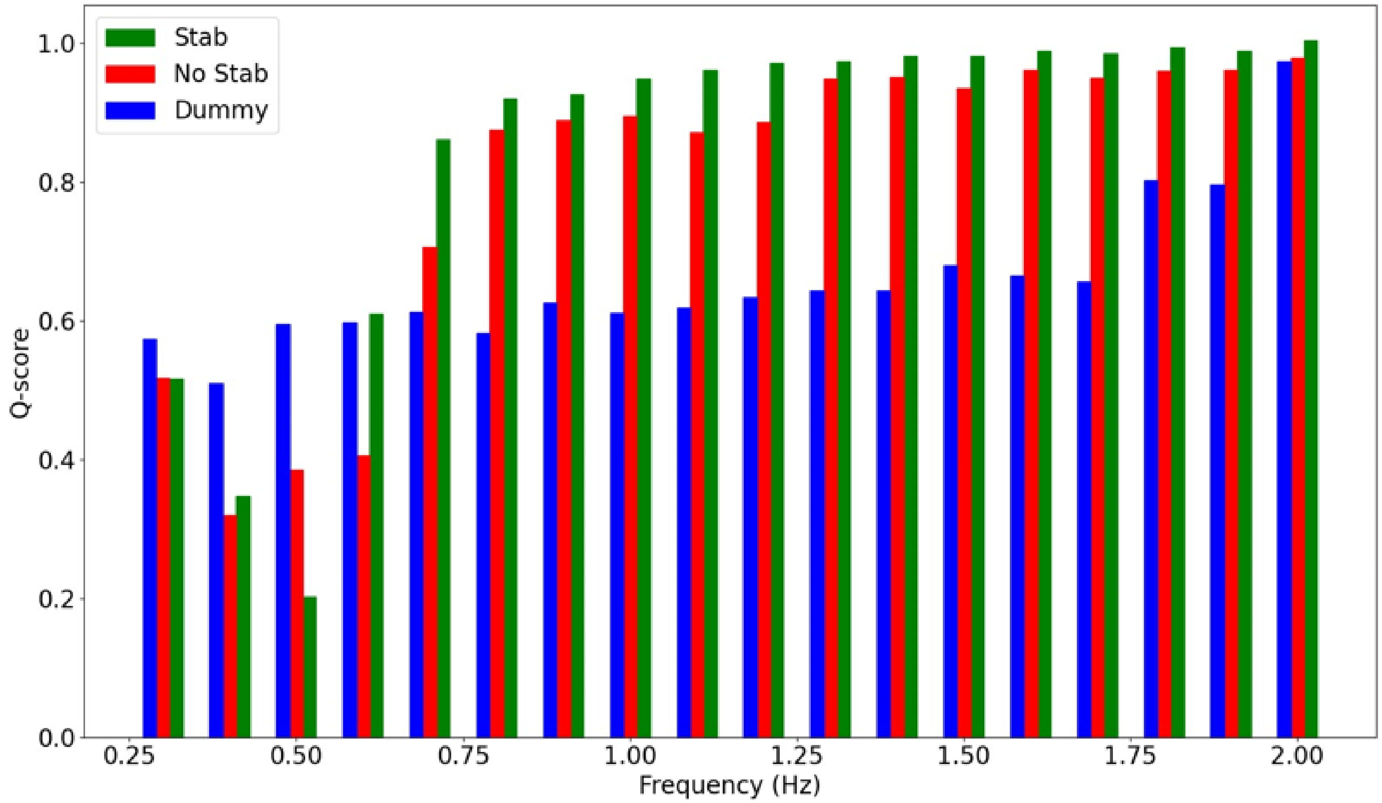
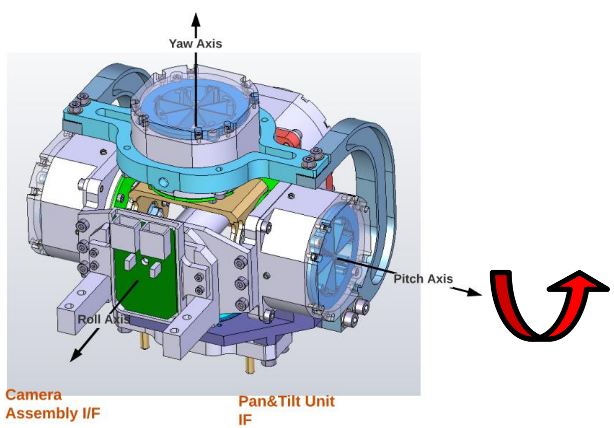
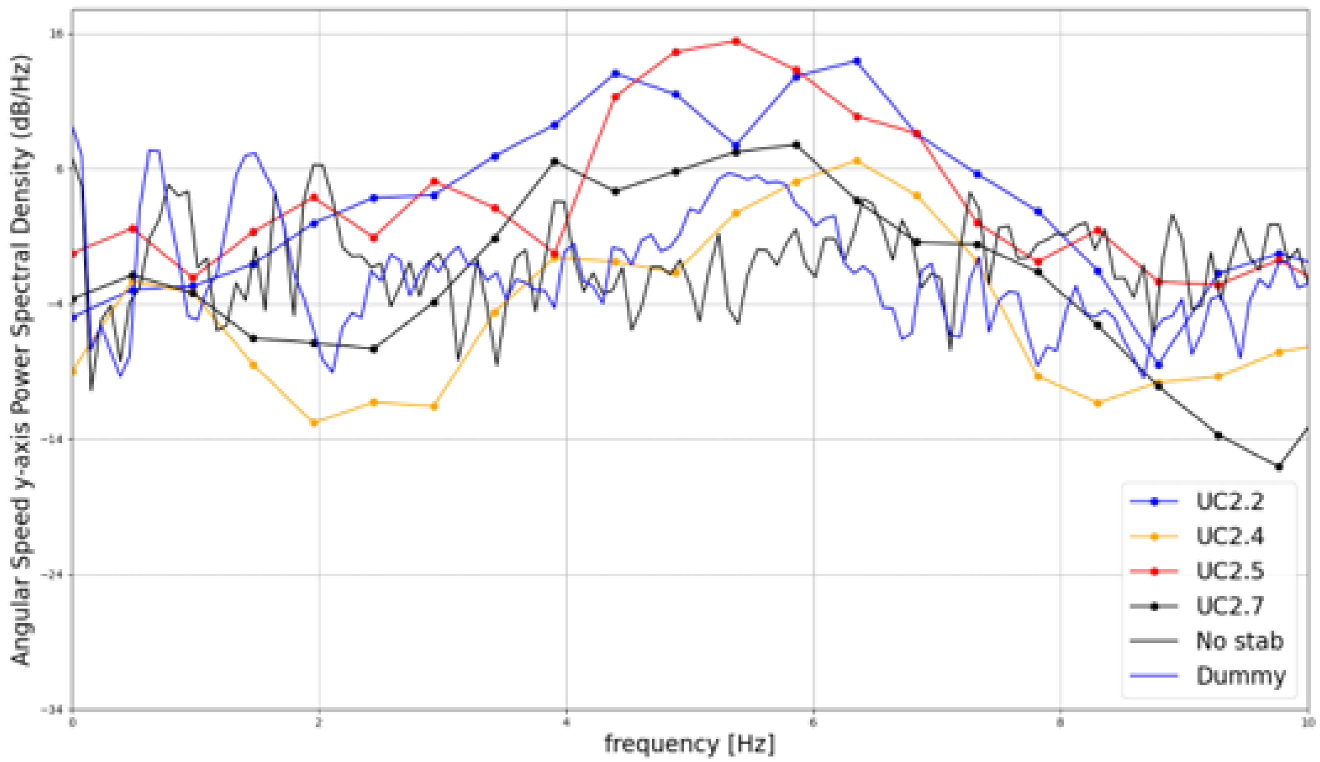


Image quality is substantially improved by STEADY for frequencies above 0.75Hz, while quality loss is detectable around 0.25Hz-0.75Hz

Analysis of Results: UC vs TC Power Spectral Density

Angular Speed Power Spectral Density comparison between UC and IMU1 (input) Pitch Sweep data

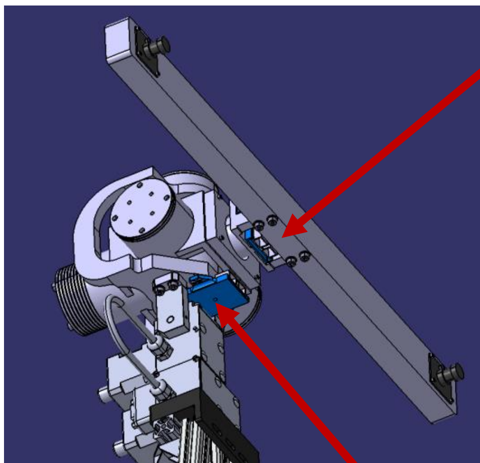




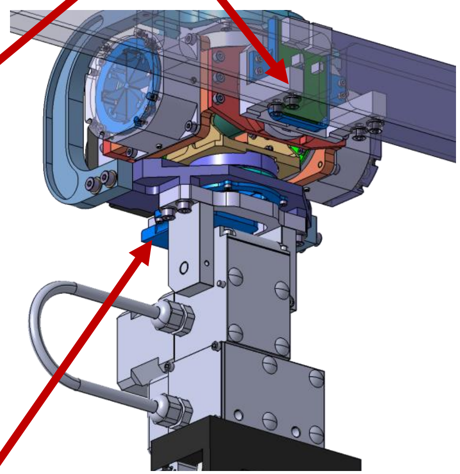
Analysis of Results: PITCH Power Spectral Density

PITCH sine sweep Averaged Angular Speed Power Spectral Density comparison.

IMU 2 (Camera I/F)

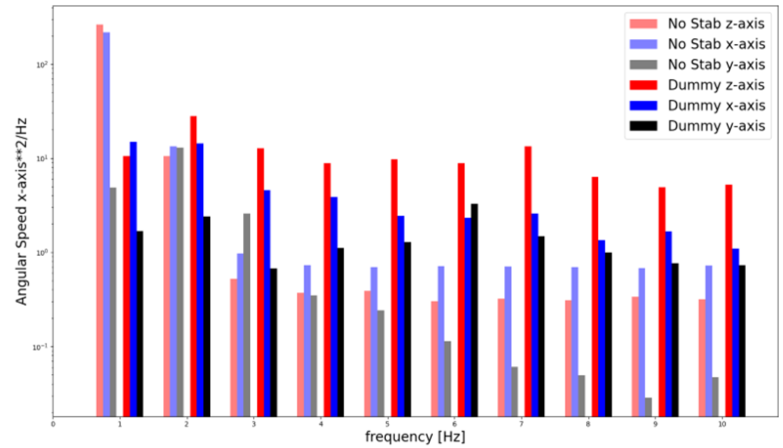


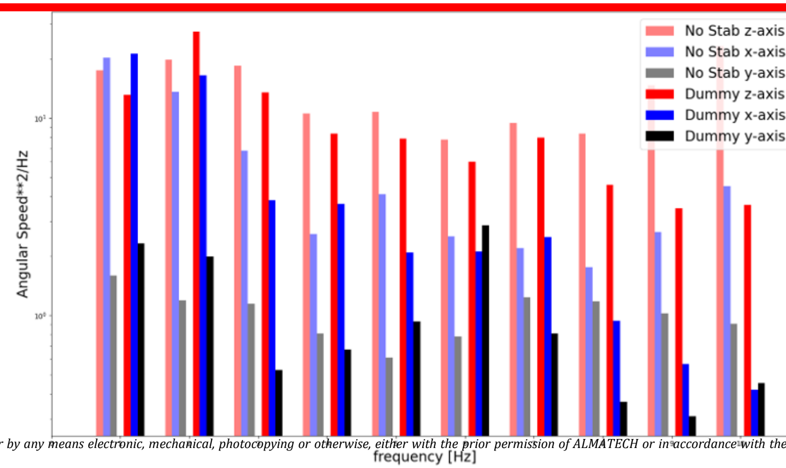
Dummy



STEADY

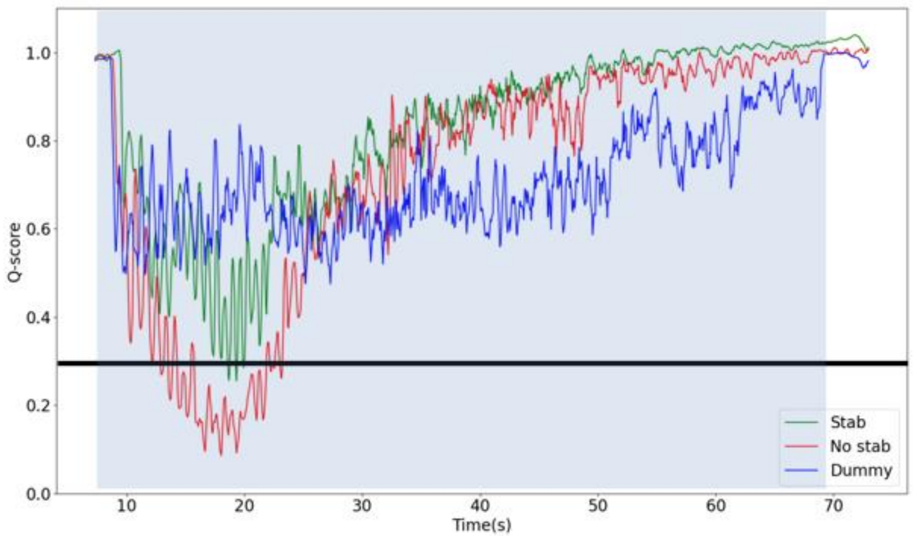
IMU 1 (input)

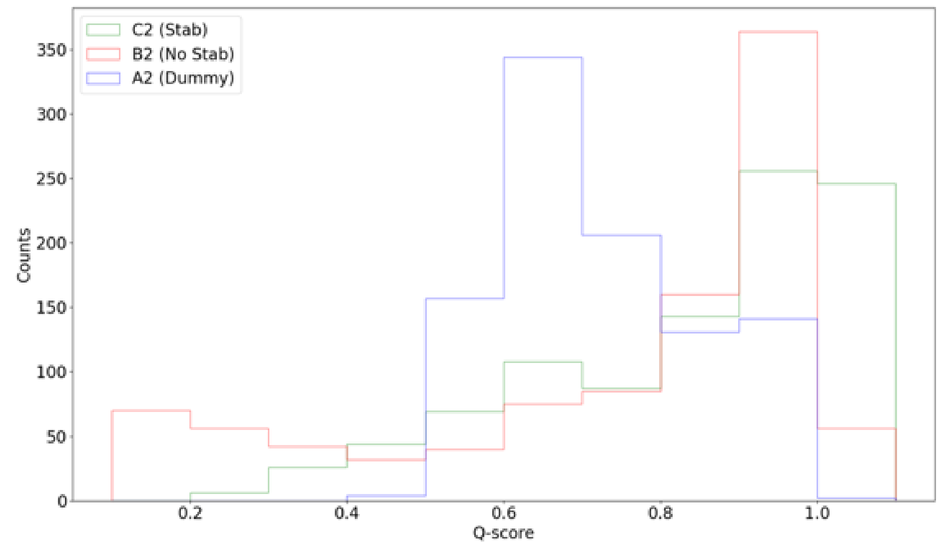




Analysis of Results: PITCH sweep comparison

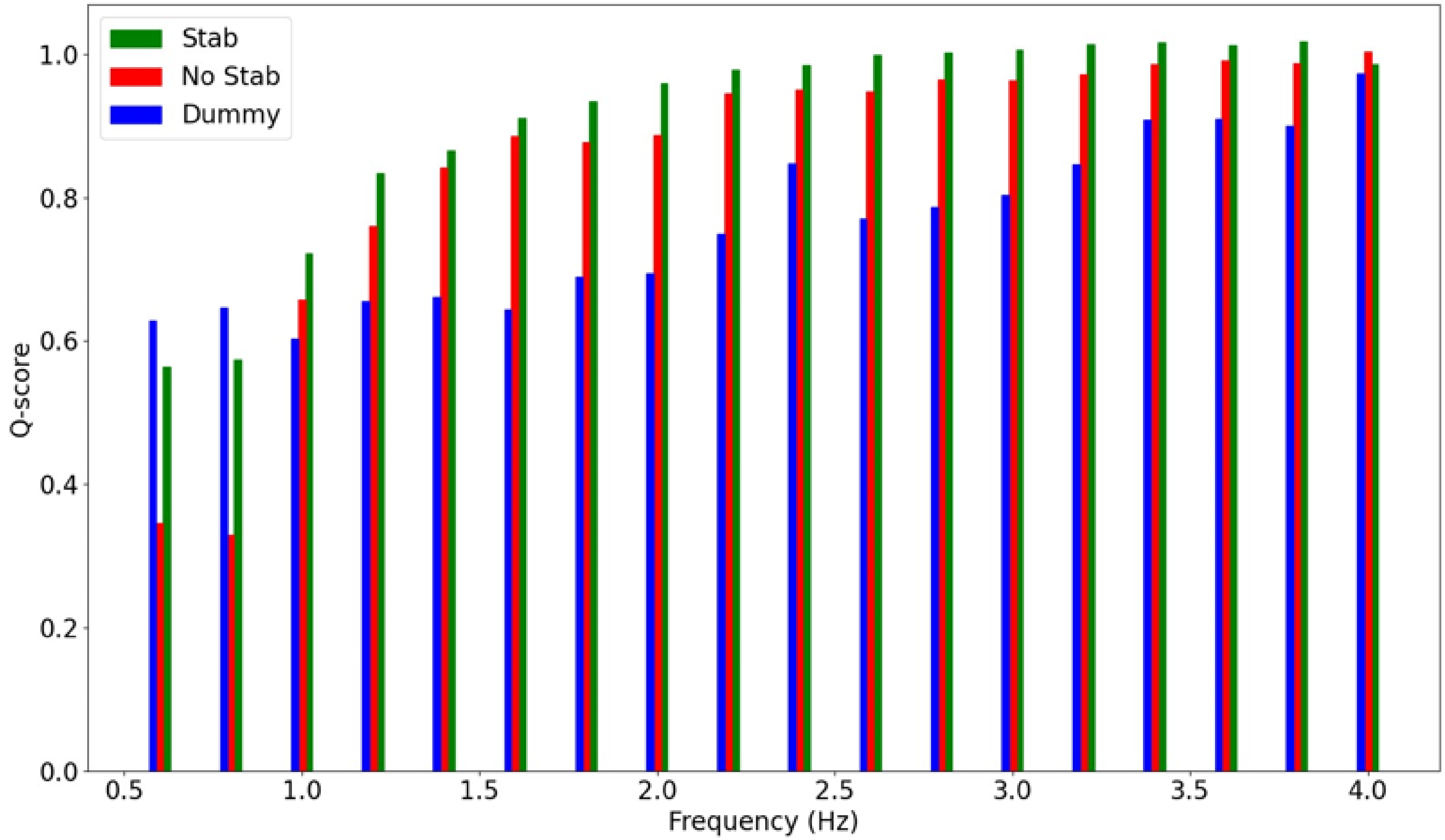
A vs B vs C (Q-score, **PITCH** sweep) & Q-scores histogram distributions





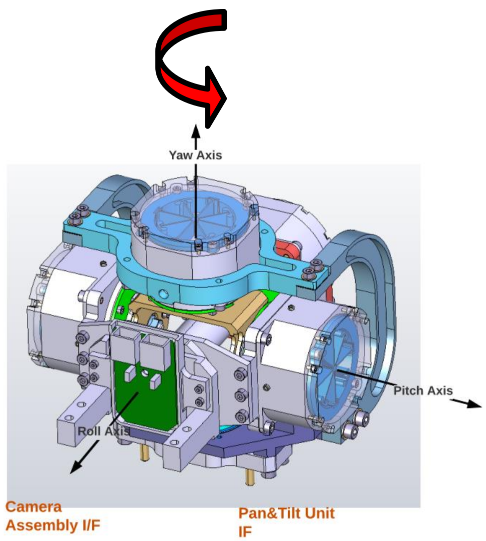
Analysis of Results: Q-score PITCH sweep

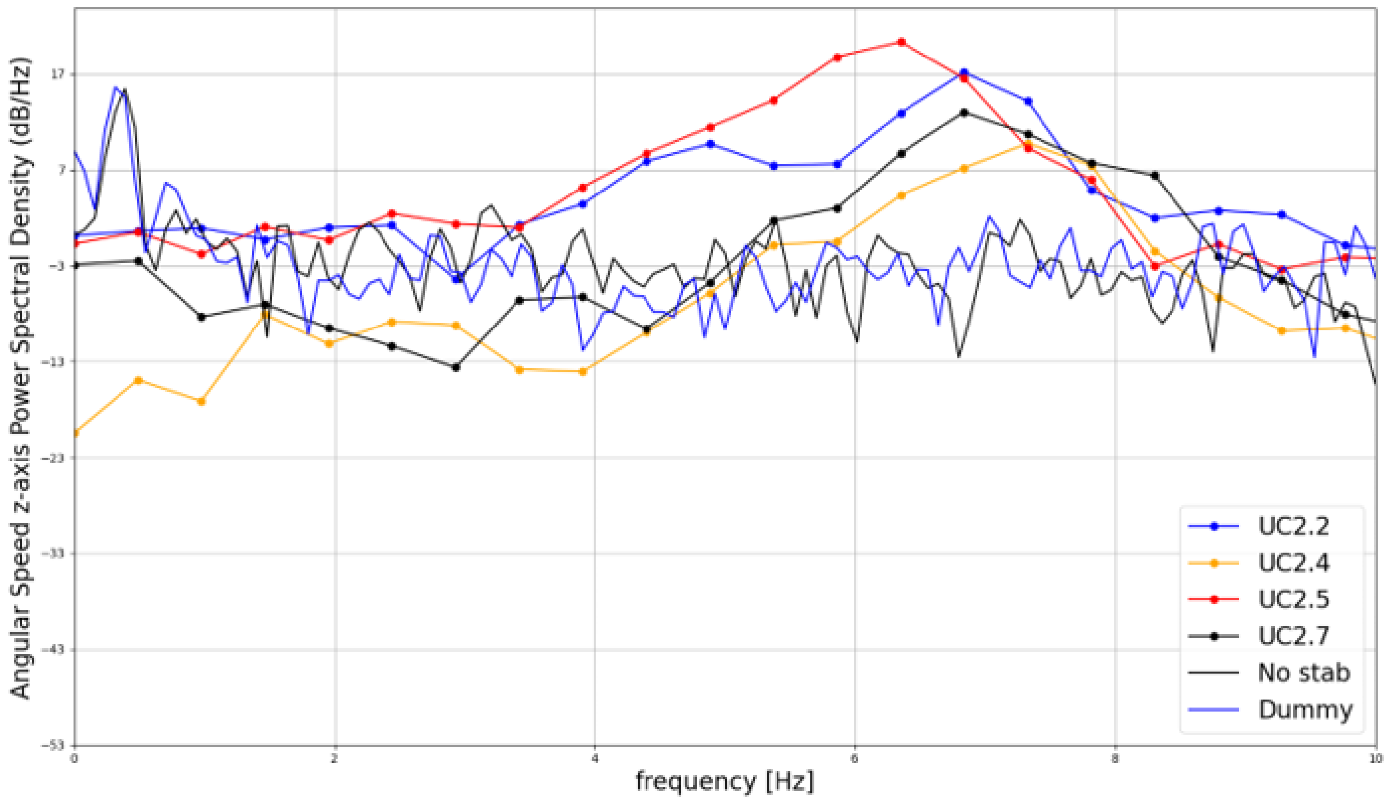
Image quality (Q-score) vs. input disturbance frequency. PITCH sine sweep.



Analysis of Results: UC vs TC Power Spectral Density

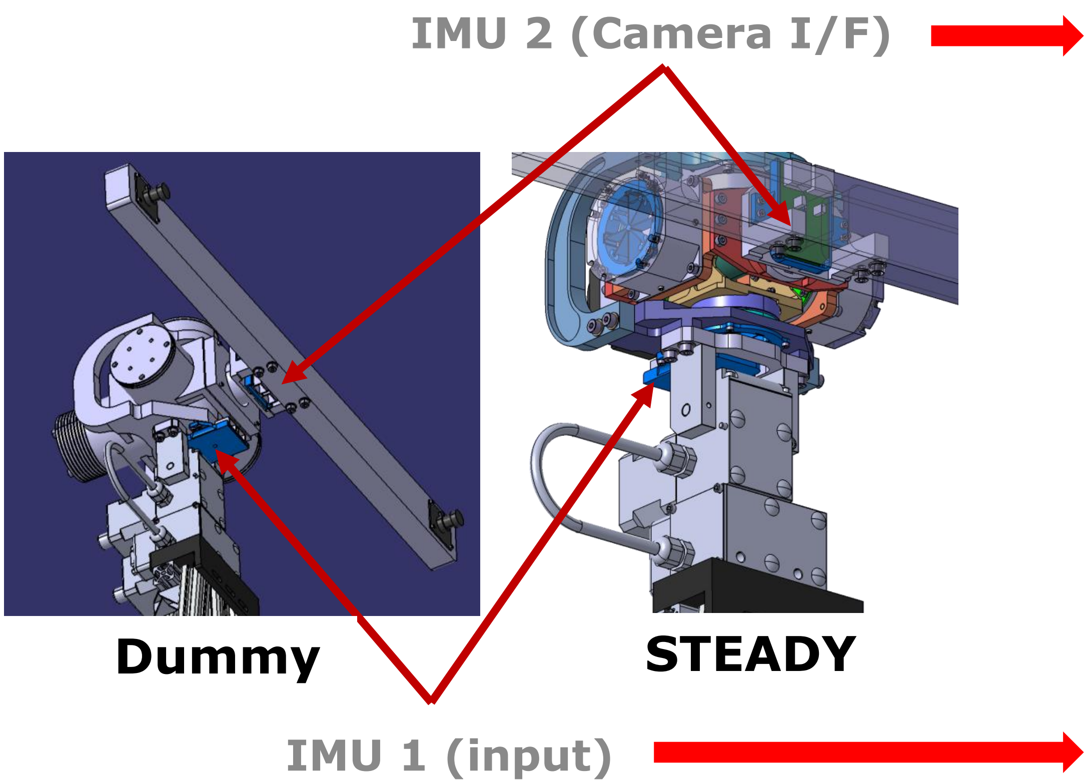
Angular Speed Power Spectral Density comparison between UC and IMU1 (input) Yaw Sweep data

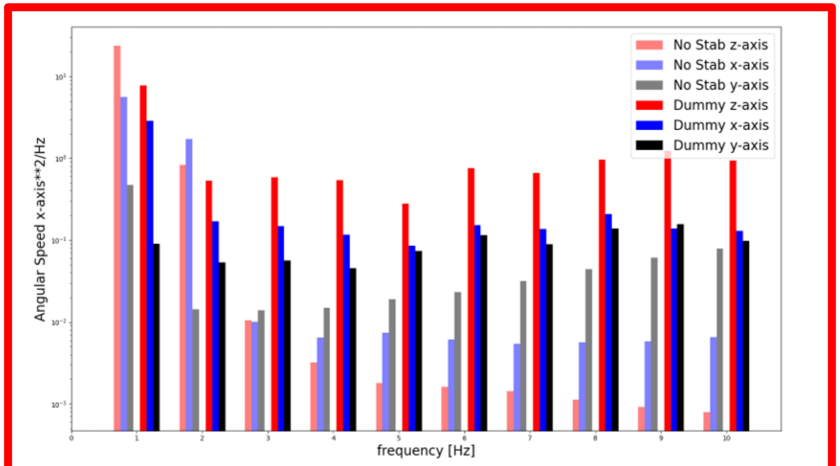


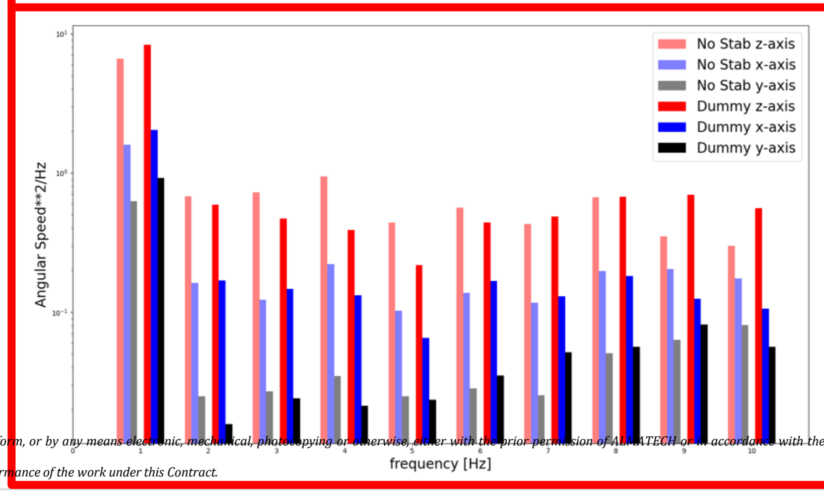


Analysis of Results: YAW Power Spectral Density

YAW sine sweep Averaged Angular Speed Power Spectral Density comparison.

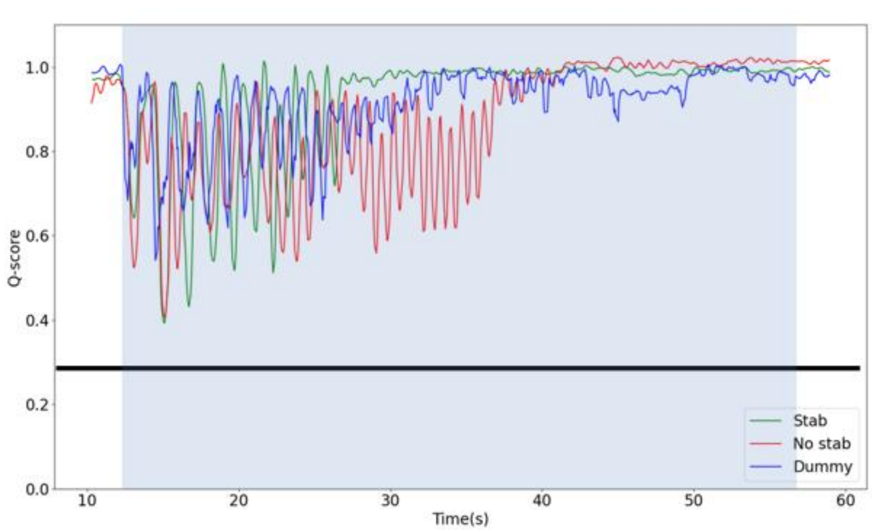


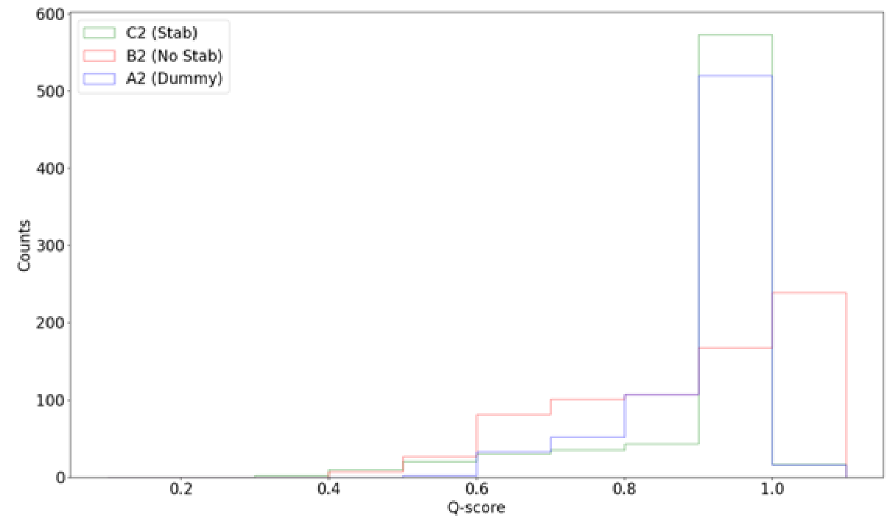




Analysis of Results: YAW sweep comparison

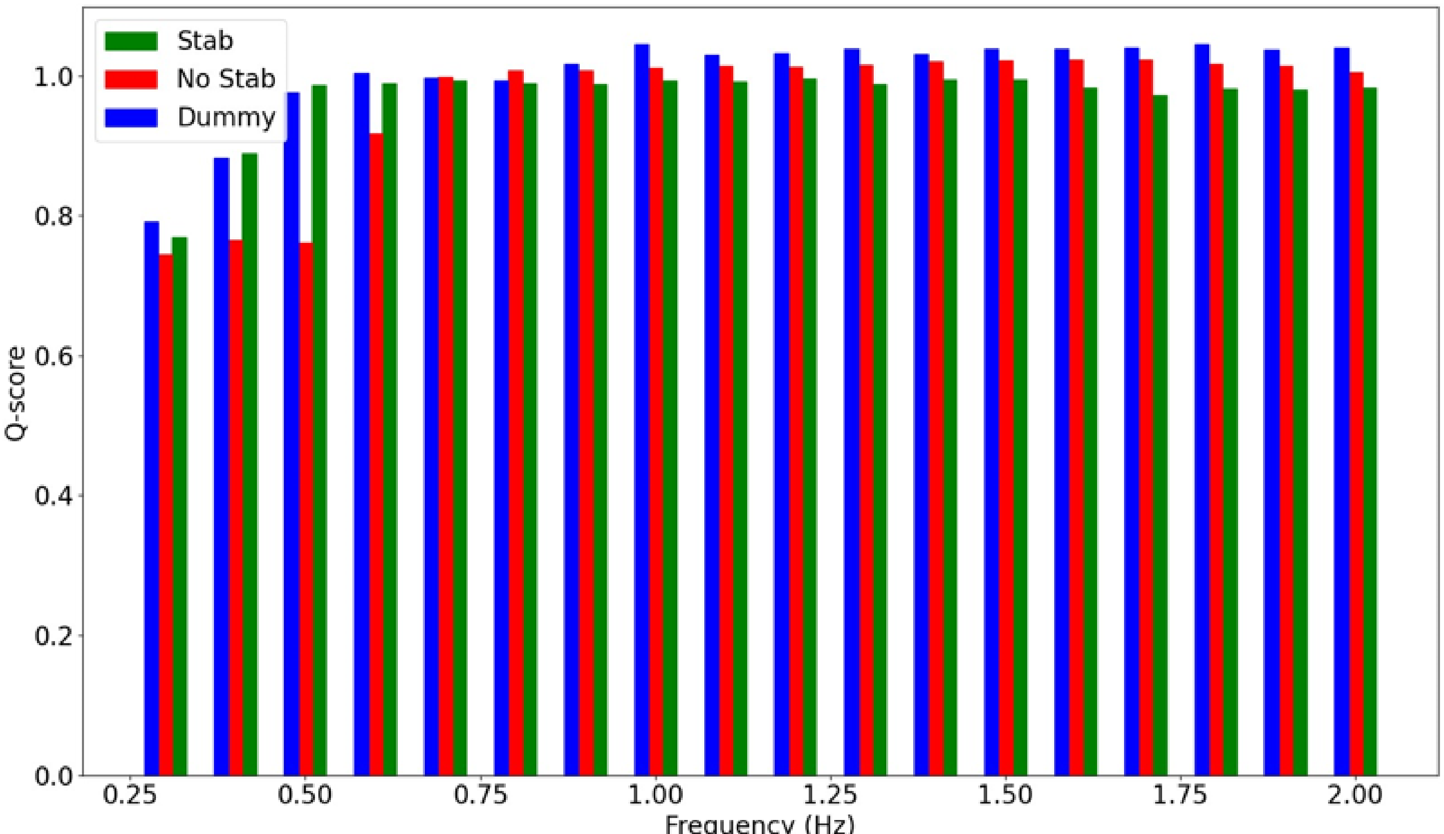
A vs B vs C (Q-score, **YAW** sine sweep) & Q-scores histogram distributions





Analysis of Results: Q-score YAW sweep

Image quality (Q-score) vs. input disturbance frequency. YAW sine sweep.



Test Results – Summary of Performances

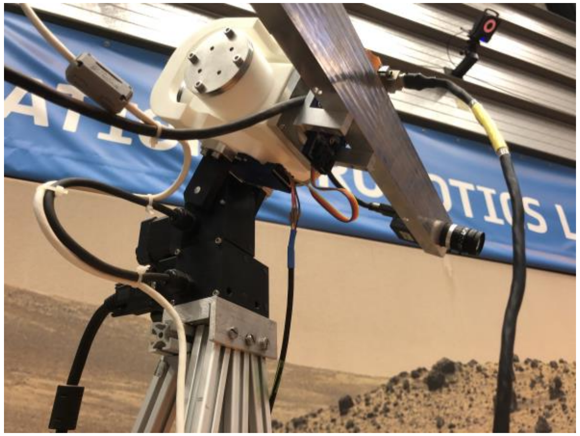
Average Image quality (Q-score) over a specific run

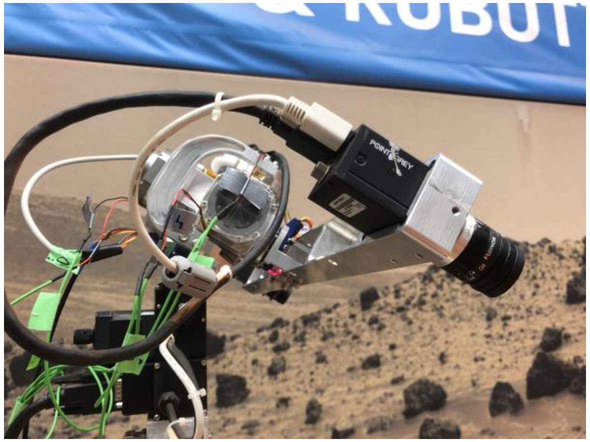
E Sequence	Dummy	No Stabilized	Stabilized
E1 Roll	0.64	0.70	0.73
E1 Pitch	0.73	0.74	0.83
E1 Yaw	0.92	0.88	0.93
TC10	0.69	0.74	0.80
TC11	0.60	0.62	0.71
TC12	0.56	0.32	0.52
TC13	0.62	0.38	0.66

Demonstration at Planetary Robotics Lab

Two sets of runs:

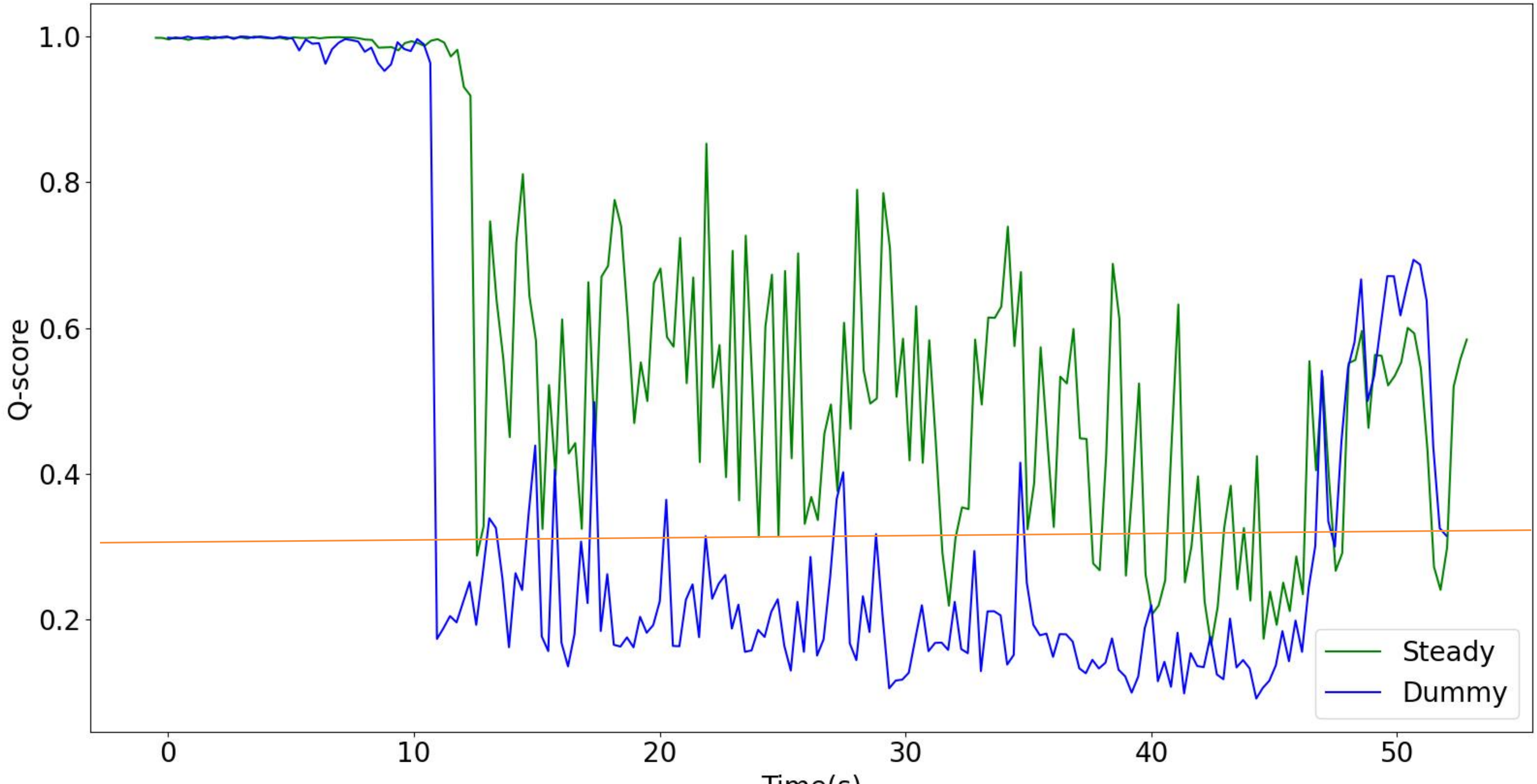
- A reference set (5 runs per set), executed with the 'Dummy' device (fixed mounting, similar inertial properties)
- Stabilized set (same runs), with the Device
- Runs:
    - Soft, 0.1m/s
    - Pebbles, 0.1 m/s and 0.3 m/s
    - Tiles, 0.1 m/s



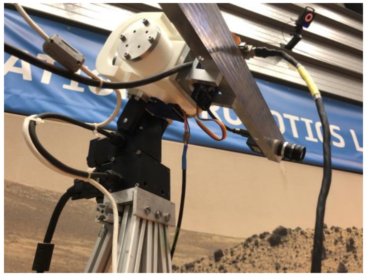


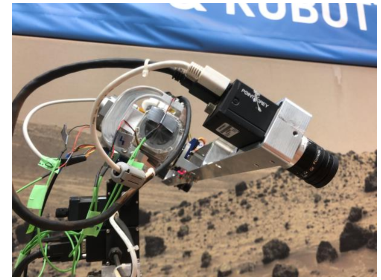
Demonstration at PRL: Preliminary Data Analysis

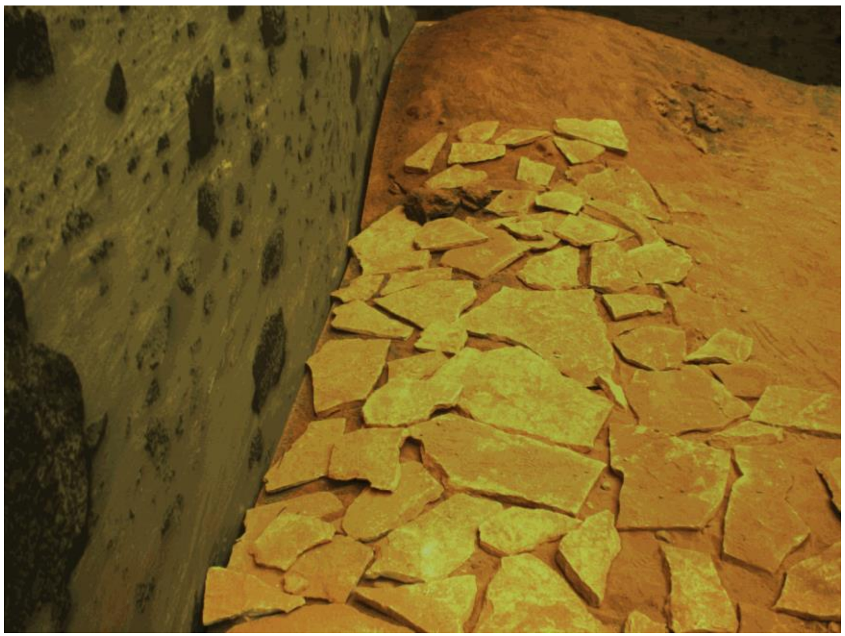
Camera Q-score comparison for ‘tiles, 0.1 m/s’

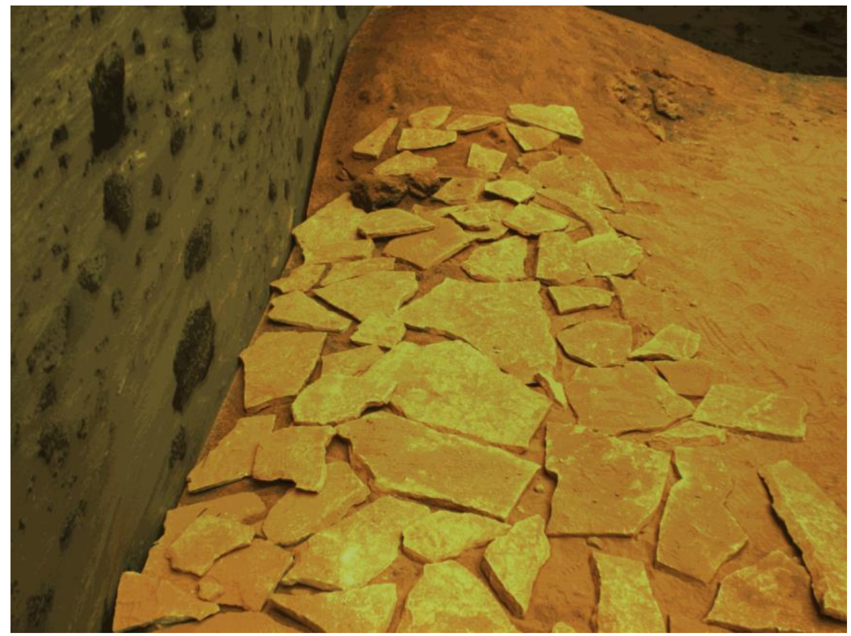


Demonstration at PRL: Camera Videos









Conclusions (1/2)

1. Definition of a general methodology to derive the requirements specifications in terms of:
   a. Image quality target (Q-score)
   b. Relationship between (camera) motion and image quality
   c. Reduction of motion transmitted from the rover to the camera (with STEADY contribution)

2. Successful reproduction of ‘vibration environment’ for verification testing
   - Benchmark sinusoidal motion (more demanding in terms of angular speeds than use cases)
   - Reproduction of ‘Runs’ (Rover use cases) is achieved with the expected limitations in achievable linear accelerations (spectral content above 8Hz is hardly achievable with the testbed – hexapod)

Conclusions (2/2)

3. Assessment of performances:
    - STEADY enables on average enhancement of image quality. The enhancement is well pronounced when the unit is exposed to a frequency content above 0.75 Hz, where the coordinated action of the control system and the natural mechanical response allow for good stabilization

4. Design Features & Improvements
    - Parametric design approach with identification of key requirements
    - Possible future improvements, primarily related to the ‘mission’

What's next for STEADY?

Next…

Thank you for your Attention