Autonomous image coverage and sharpness detection for fly-by missions

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Introduction We present an in-flight image coverage and sharpness detection for download prioritization as implemented in Milani/Hera mission. Hera [1] is the European part of the Asteroid Impact & Deflection Assessment (AIDA) project with NASA who is responsible for the DART (Double Asteroid Redirection Test) kinetic impactor spacecraft impacting Didymos/Dimorphos binary asteroid in January 2022. Hera will be launched in October 2024 and will arrive at Didymos in 2027. Milani 6U CubeSat [2] will be carried by Hera and is developed by a Czech-Finnish-Italian consortium. Milani has two payloads – ASPECT hyperspectral imager and VISTA thermogravimeter and aims to characterize surface and environment surrounding Didymos with special focus to map DART impact site from distance of 10 km down to 5 km.

ASPECT hyperspectral imager ASPECT is a hyperspectral imaging spectrometer [3] developed by VTT Technical Research Centre of Finland. Its key component is a tunable Fabry-Pérot Interferometer (FPI). ASPECT has spectral range from 500 nm up to 2500 nm divided into 4 measurement channels. VIS and NIR1/2 channels have imaging capability, while the SWIR channel is a single point spectrometer. Fe^{2+} absorptions, in dry silicates at ~1 and ~2 µm, Fe^{3+} absorption in hydrated silicates at ~0.7 µm, -OH absorption at ~1.4 µm, and H_2O absorption at ~1.9 µm are all found within the ASPECT spectral range.

ASPECT imaging strategy and on-board algorithms for image quality detection A dedicated DPU (Data Processing Unit) based on Xiphos Q7S is integrated with ASPECT. Its function is to (1) autonomously execute pre-programmed hyperspectral data capture sequences, (2) reconstruct hyperspectral images from the raw data stream and store them in internal memory, (3) run set of pre-programmed algorithms to autonomously evaluate coverage and sharpness of the hyperspectral data cubes in order to select highest-quality data cubes for download to ground, and to (4) compress downloaded data using lossless or near-lossless JPEG2000 compression. These features enable ASPECT imaging strategy based on performing multiple hyperspectral data cube acquisitions of each scene (target asteroid orientation) and selecting the highest-quality data meeting criteria on coverage and sharpness for download. The DPU algorithms contain flexible configuration settings to modify or bypass features through ground commanding. This enables in-flight algorithm optimization based on actual target appearance (e.g., albedo variations, surface features) and ASPECT imager performance (e.g., noise levels, exposure time).

Algorithm architecture The image quality detection algorithm architecture is depicted in Fig. 1 and consists from four main blocks: **(1)** Global pixel statistics for global coverage evaluation, **(2)** Areal pixel statistics for coverage evaluation of individual objects (Didymos D1 vs. Dimorphos D2), **(3)** Laplacian filter convolution for sharpness detection, and **(4)** Artificial Intelligence (AI) experimental code for coverage and sharpness scoring. On input side single image from each datacube (at 500 nm, reconstructed from VIS channel RGB sensor green pixels) is extracted for quality check. This selection was based on the expected ASPECT high signal-to-noise ratio in this spectral region. Optional Gaussian convolution filter can be activated to remove noise. This step is important for proper coverage evaluation of images with substantial noise (where noise can confuse pixels statistics) but is skipped for sharpness evaluation and AI code (as Gaussian filter convolution intrinsically softens image boundaries). On output side, the individual coverage, sharpness, and AI scores are combined by decision logic as outlined in Fig. 1 and decision on data download is made. In the case the required object coverage is reached, the data cube with the highest combined Image Quality Score (IQS) and AI scores is downloaded together with metadata. In the case the required object coverage was not reached, only metadata with image thumbnails are downloaded for detailed analysis on ground. The metadata contain information on pixel statistics thresholds as well as compressed Laplacian histograms and compressed evaluation image thumbnails. This enables to monitor the algorithm behavior on ground and adjust algorithm settings by commanding.

Pixel statistics For object coverage detection, thresholding is used to identify asteroids and coverage. As a threshold, we use weighted sum of two different algorithms and optional fixed threshold settings (relative or absolute). Apart from the standard Otsu thresholding algorithm [4] we developed one custom tresholding for bright objects on black background based on the histogram shape. Either global pixel coverage is evaluated without object detection or object (D1 or D2) detection can be accomplished based on area selection using criteria like object size, shape, relative position of binary components, or pixel density. Final coverage is normalized to [0,1] interval and compared to desired minimum required asteroid coverage to check if desired coverage was achieved.

Laplacian filter convolution For sharpness detection, Laplacian filter convolution as a proxy to image second derivative provides reliable results because it is sensitive to sharp contrast boundaries within the image. Images with sharp boundaries have wider Laplacian histogram with higher maximal Laplacian values compared to smeared images where the histogram width and maximal Laplacian values are relatively reduced. Thus, the highest Laplacian values are used as an indicator of relative sharpness within an image series. The output is normalized into relative sharpness score in the range of [0,1].

AI experimental algorithm Two multi-label Convolutional Neural Networks (CNNs) have are implemented, one for ranking images according to their coverage, and another according to their sharpness. The input images of the coverage CNN are reduced to 128x128 pixels to save DPU resources. The input is passed through three consecutive convolutional layers ending with a dense layer that outputs the selected coverage and sharpness labels as values from 1 to 4. The training sets consist of synthetic images of the Didymos/Dimorphos system created with a custom Python/Blender pipeline and with variations in coverage and sharpness added in post-processing.

Ground commanding and metadata content Input configuration parameters are used to adjust the image scoring pipeline behavior in flight to either change basic building block behavior and/or to modify how elementary results are used in upper levels to produce final IQS. To monitor the image scoring output metadata containing partial results are used to monitor each building block separately. Examples of input parameters and output metadata are:

Input parameters	Output metadata
• Thresholding weights • Image border size • Sharpness and coverage weights for final IQS • Enable/disable noise filtering for coverage tests • Coverage detection mode (All, D1, D2, D1+D2) • Desired minimum asteroid coverage	• Compressed Laplacian histogram • Partial threshold values, final threshold used • Coverage statistics (coverage, border) • Sharpness result (Laplacian histogram max.) • Normalized coverage and sharpness • Neural Network sharpness and coverage values

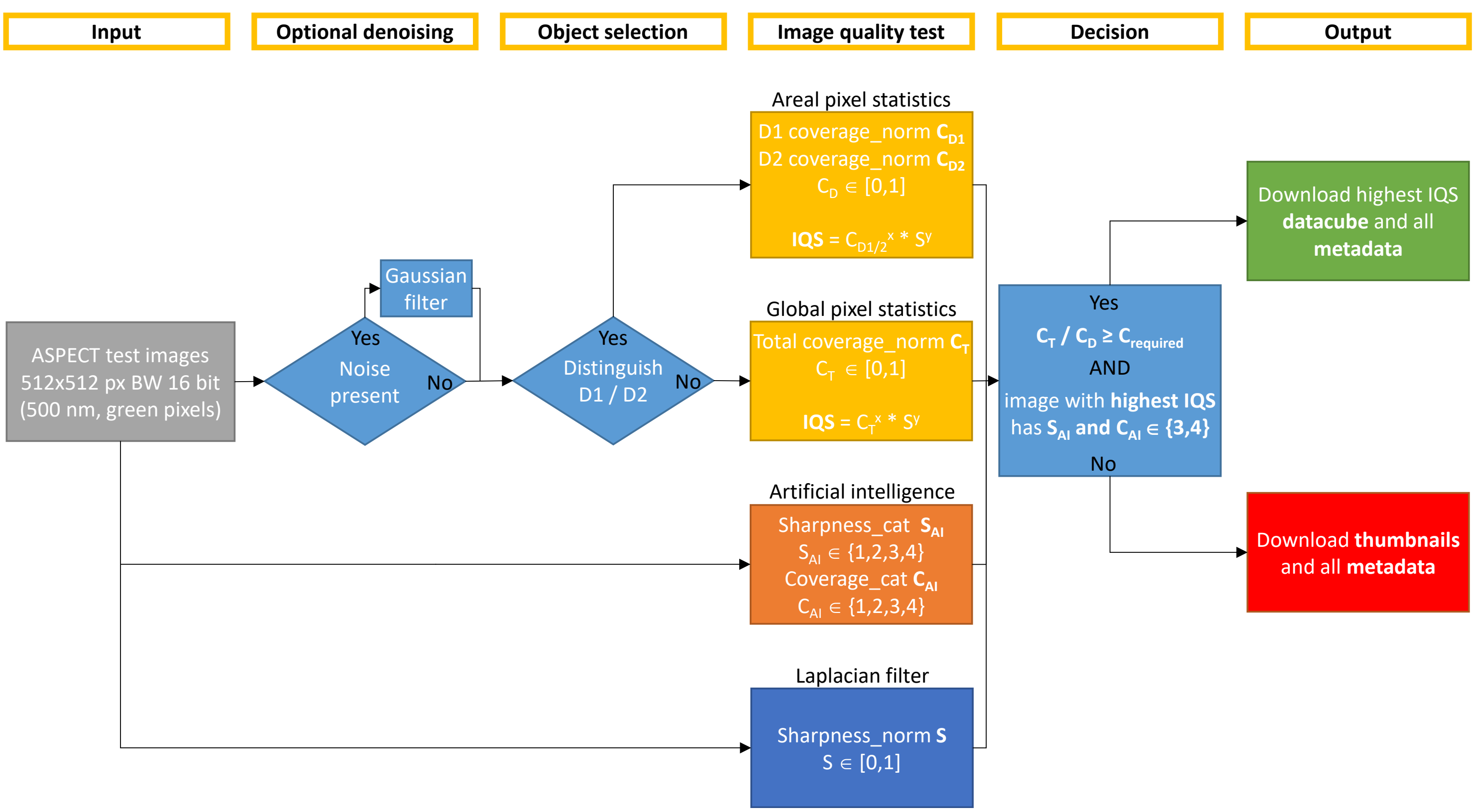

Fig. 1. On-board image quality detection algorithm architecture.

References: [1] https://meetingorganizer.copernicus.org/EPSC2021/EPSC2021-71.html [2] https://meetingorganizer.copernicus.org/EPSC2021/EPSC2021-732.html [3] https://ieeexplore.ieee.org/document/9172437 [4] https://ieeexplore.ieee.org/document/4310076