# Flight Testing a Vision-Based Navigation and Hazard Detection and Avoidance (VN&HDA) Experiment over a Mars-Representative Terrain

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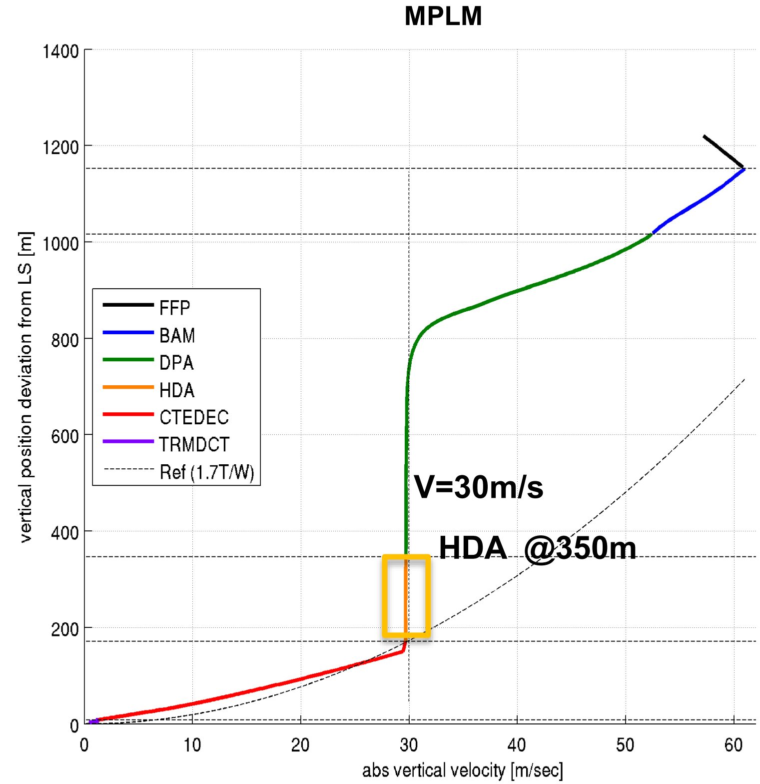
# INTRODUCTION

# Sensor Data Fusion for Hazard Mapping and Piloting (FUSION)

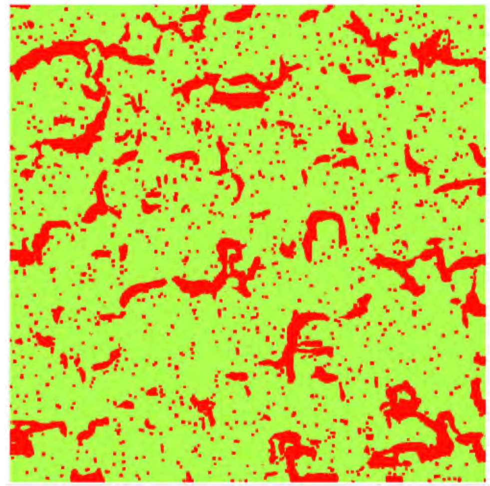
- Statistically demonstrated probability >99% of safe landing on the surface of Mars
  - Functional Engineering Simulations
  - Perfect Navigation
- Mission design:
  - Mars Precision Landing Mission (MPLM) descent profile
    - Start at Free-Fall Phase (FFP) after parachute cut-off
    - Back-shell Avoidance Manoeuvre (BAM)
    - Descent Profile Acquisiton (30 m/s)
    - Trigger Hazard Detection and Avoidance (HDA) at h=350m AGL (LIDAR operational limit)
    - Allow 10 seconds for HDA to return Selected Landing Site (SLS)
    - Retarget manoeuvre to SLS and decelerate to landing
  - Sensor suite
    - IMU, Radar Altimeter, Camera, LIDAR



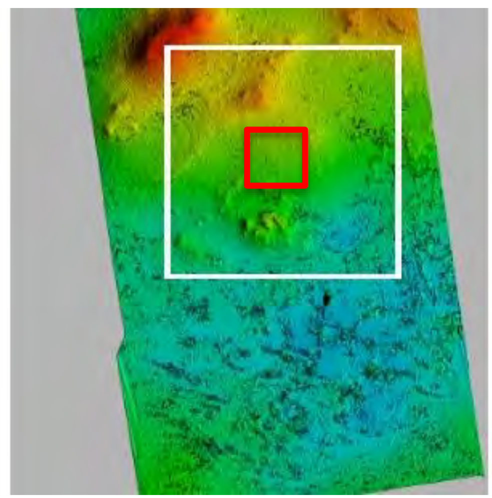
## INTRODUCTION – Sensor Data Fusion for Hazard Mapping and Piloting

# Mars Representative Terrains

- -4 Synthetic Martian terrains
- -Example Terrain
  - -Mars Nili
  - -6.9% rock distribution
  - -Safe blind landing probability ~80%



| | Sun elevation angle | | |
|---|---|---|---|
| | 25 deg | 50 deg | 70 deg |
| Slope safety rate | 85.57% | 85.57% | 85.57% |
| Roughness safety rate | 94.00% | 94.00% | 94.00% |
| Illumination safety rate | 98.47% | 99.97% | 99.95% |
| Global safety rate | 79.96% | 80.51% | 80.51% |

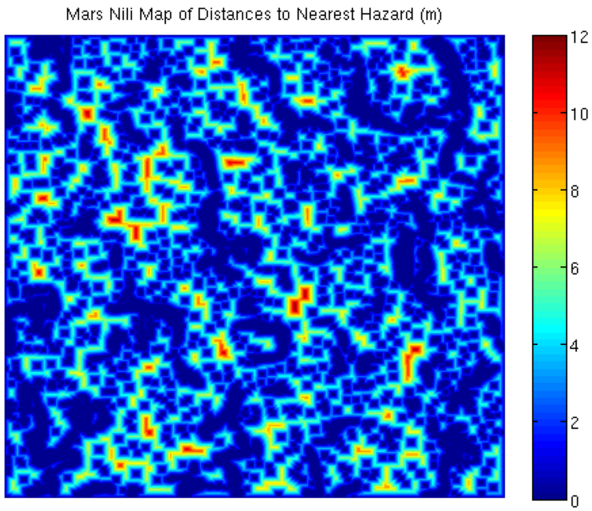


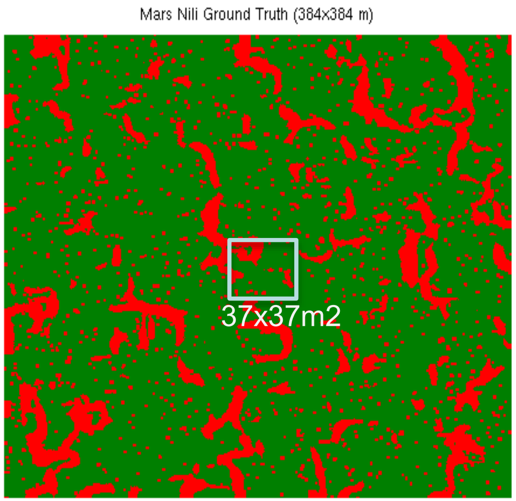
Mars Nili terrain model

INTRODUCTION – Sensor Data Fusion for Hazard Mapping and Piloting

# Mars Representative Terrains

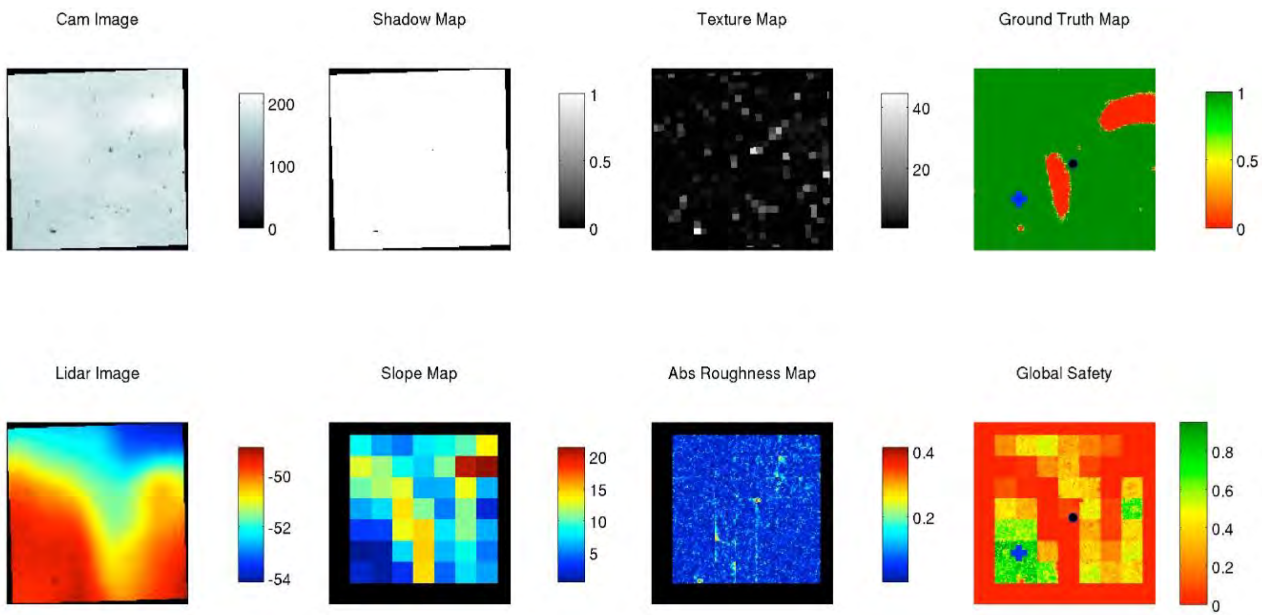
- -HDA Global Hazard Map
  - -37x37 m2 area where LIDAR & Camera image are available
  - -29 cm/pix resolution
  - -Retargeting manoeuvres <26m offset
- -Rock hazard set to >30cm height
- -Slope hazard set to >15deg slope

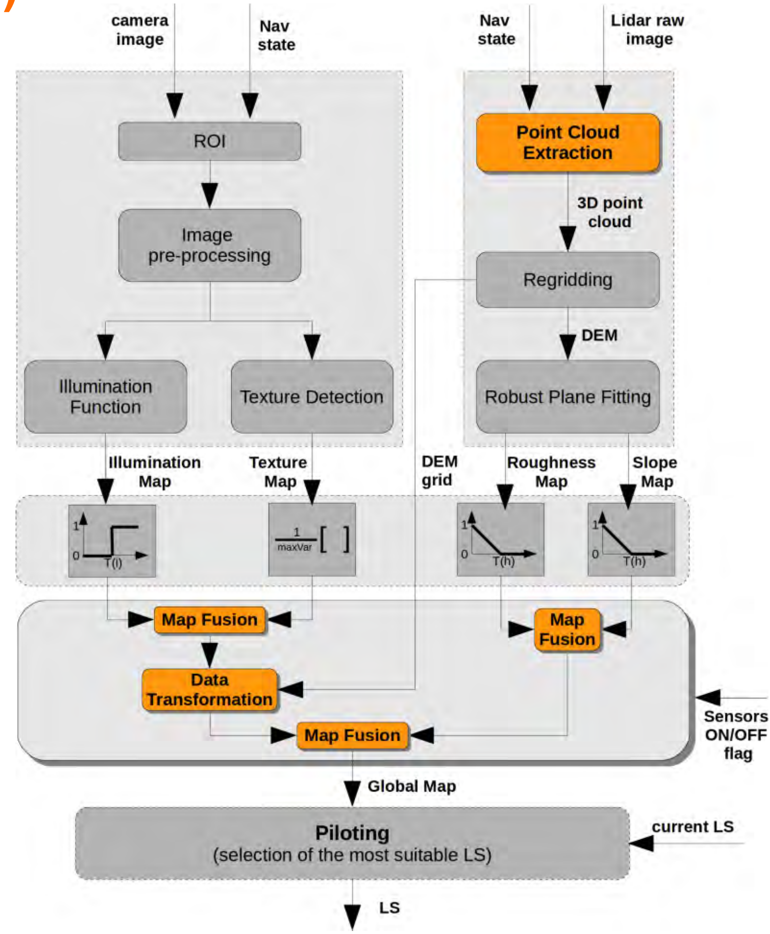



# Hybrid Hazard Detection and Avoidance ($H^2DAS$)

- Complete camera-LIDAR HDA algorithm to enable the safe landing of a planetary mission
- Returns the coordinates of the most suitable landing site



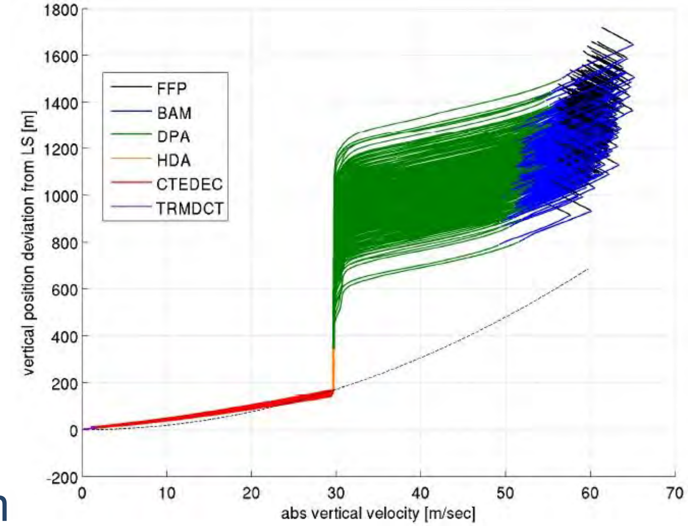



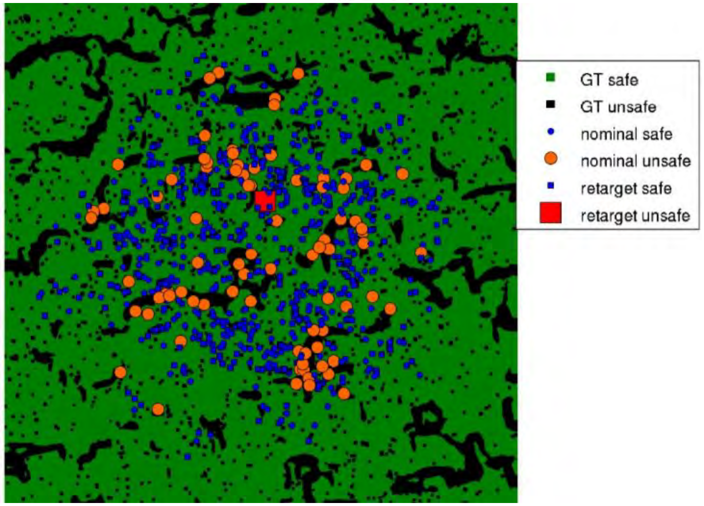

  

## INTRODUCTION – Sensor Data Fusion for Hazard Mapping and Piloting

# Monte Carlo Campaigns

- Total of 1800 simulations (450 per terrain)
- Probability of Safe Site Selection (PSSS) of 99.8% (1796/1800)
- All HDA failures due to miss-detection of small rocks, near the safety threshold
- The results verify the requirement "The H²DAS system shall have a probability of safe site selection > 99%" with a confidence level of 99.9%



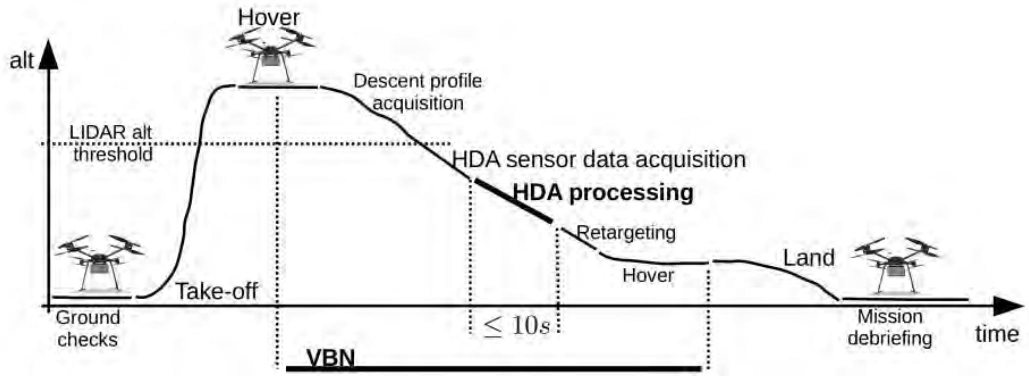

Mars Nili Ground Truth (GT) Map

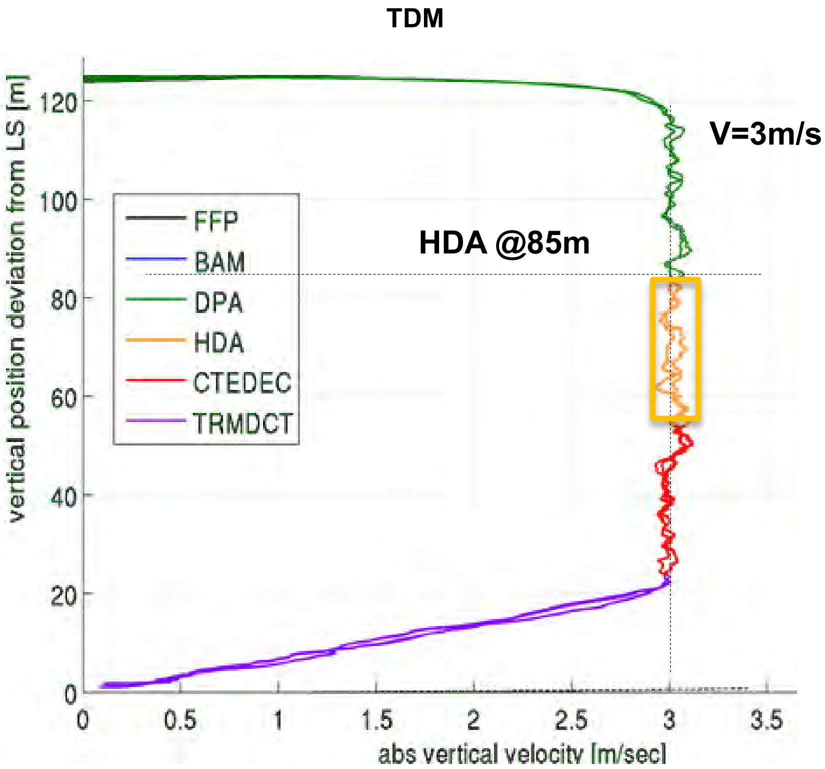
## AVoidance algorithms Extended development & Realistic Testing (AVERT)

- Consolidate/further develop data fusion algorithms
  - **Actual Flight Testing**
  - Statistically demonstrate the ability to land safely on the surface of Mars
  - Validate Visual Based Navigation (VBN) and Hazard Detection and Avoidance (HDA) algorithms
- Develop Avionics Test Bench (ATB)
  - Flight-representative HW (CPU+FPGA)
  - COTS sensor suite:
    - Camera, IMU, LRF, LIDAR
  - VN&HDA real-time software
- Flight tests
  - Terrestrial Demonstration Mission (TDM)
  - Mars representative landing mission scenario

# Terrestrial Demonstration Mission (TDM)

- Scaled mission
- Profile:
  - Begins at Descent Profile Acquisition (DPA)
- Vehicle: Multi-Copter
  - MTOW < 25Kg
  - Operational ceiling 120m (400 ft) AGL
  - Max vertical speed 5m/s
- LRF and LIDAR max range of 120m



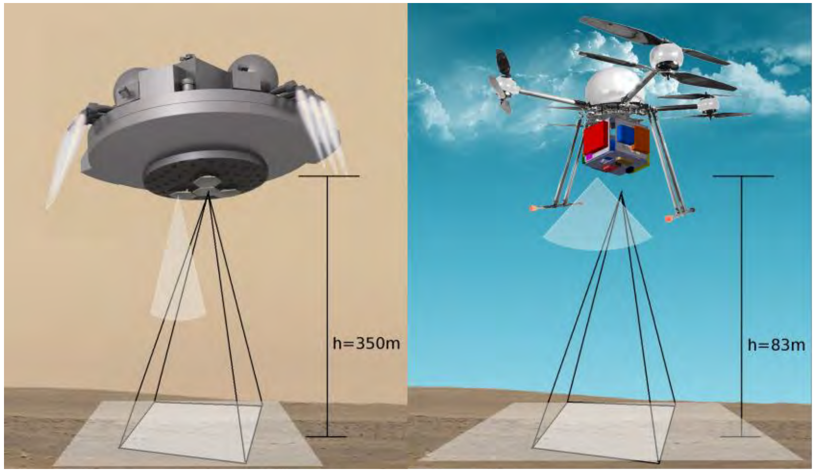

  

# Hazard Detection and Avoidance (HDA)

- Hybrid Hazard Detection and Avoidance ($H^2DAS$) algorithm
- Sensor data presented to HDA algorithm is representative of the actual MPLM mission scenario

| | LIDAR | | Camera | |
|---|---|---|---|---|
| | MPLM | TDM | MPLM | TDM |
| **Trajectory** | | | | |
| Image altitude [mAGL] | 350 | 83 | 350 | 83 |
| **Sensor** | | | | |
| Number of pixels | 128x128 | 160x160 | 512x512 | 800x600 |
| FOV (deg) | 6x6 | 32x32 | 25x25 | 101x85 |
| **Performance** | | | | |
| GSD [cm] | 29 | 29 | 30 | 25 |
| Imaged landing area size [m2] | 37 x 37 | 46 x 46 | 155 x 155 | 201 x 151 |
| Time/image [s] | 1 | 5 | 0.1 | 0.1 |
| Accuracy [cm] @ image alt | 10 | 8 | - | - |

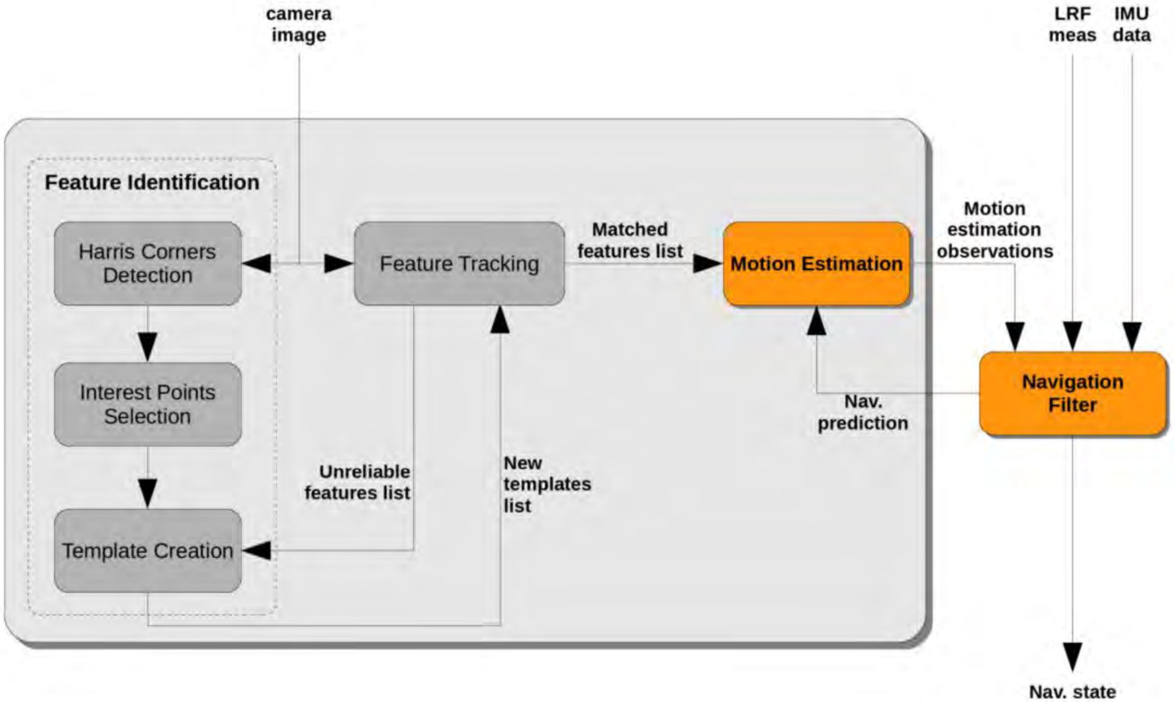
**MPLM** **TDM**



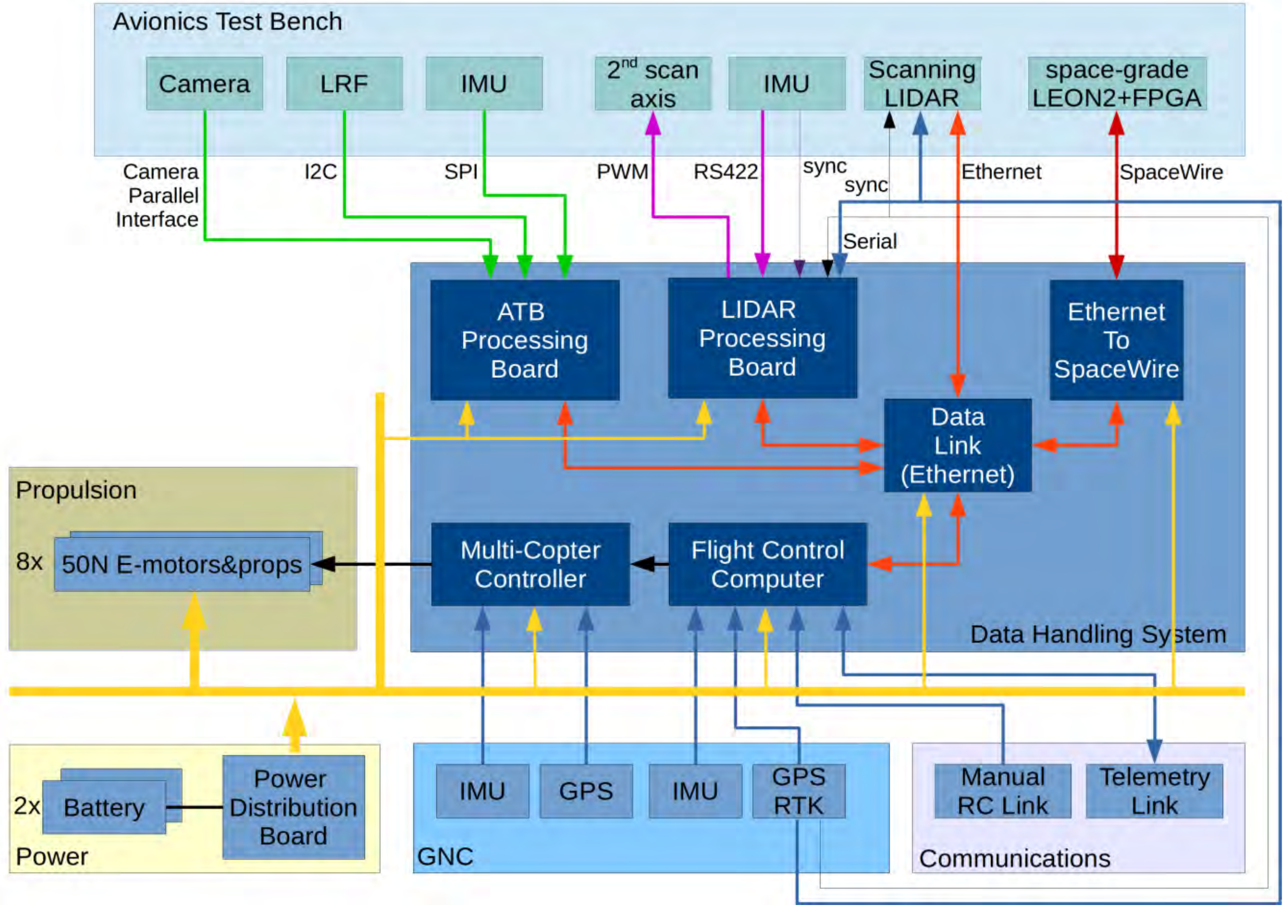
# Visual Based Navigation (VBN)

- A Camera-IMU-LRF navigation solution that delivers relative navigation estimates
- The Camera feature-tracking algorithm provides motion observations that are used to update the Navigation Filter
- The Navigation Filter performs dead-reckoning integration of IMU inputs and relies on LRF and visual-based motion estimates to update the motion states

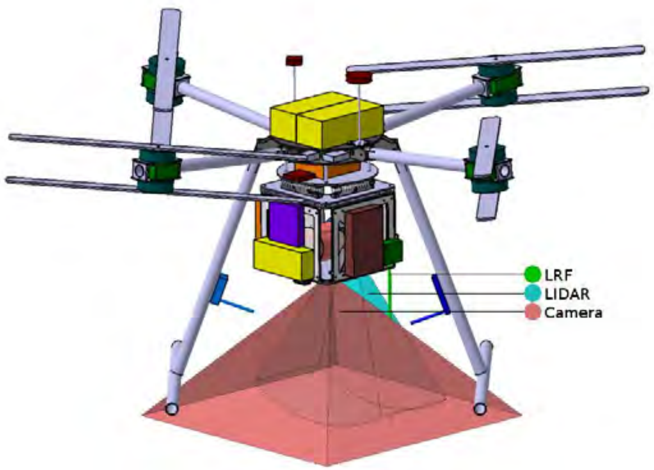


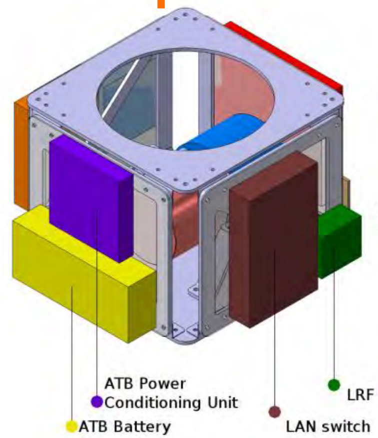
# Avionics Architecture

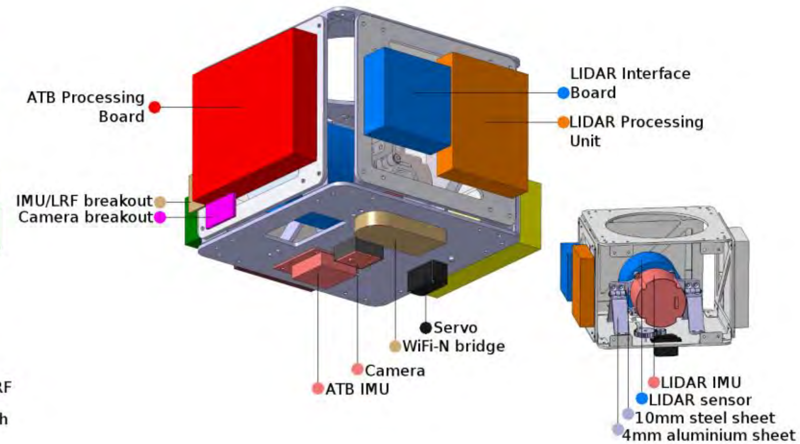
- Flight Test Platform
  - Multicopter
- Avionics Test Bench
  - Camera
  - Laser Range Finder
  - Inertial Measurement Unit
  - LIDAR
  - Space-grade LEON2+FPGA

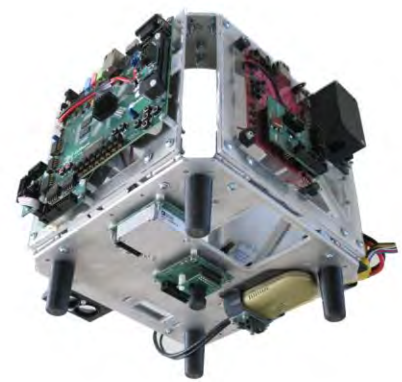


# Avionics Test Bench – Design and Implementation



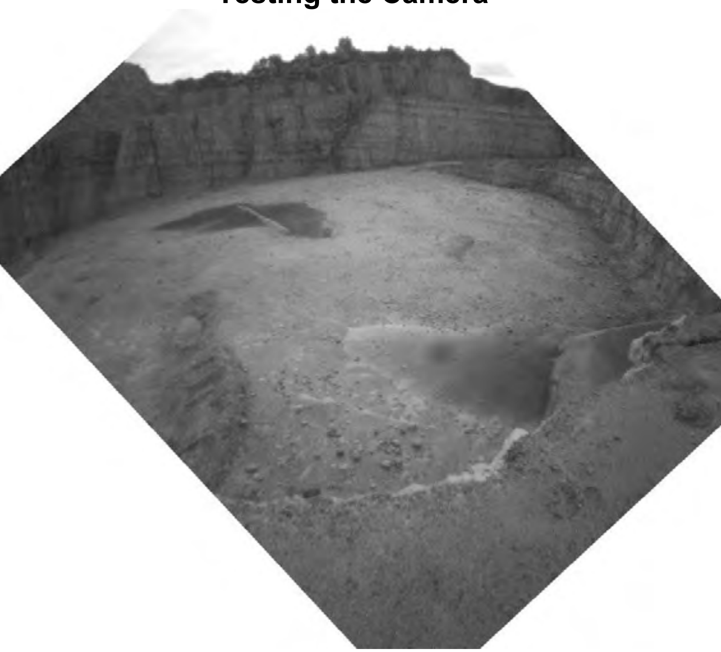



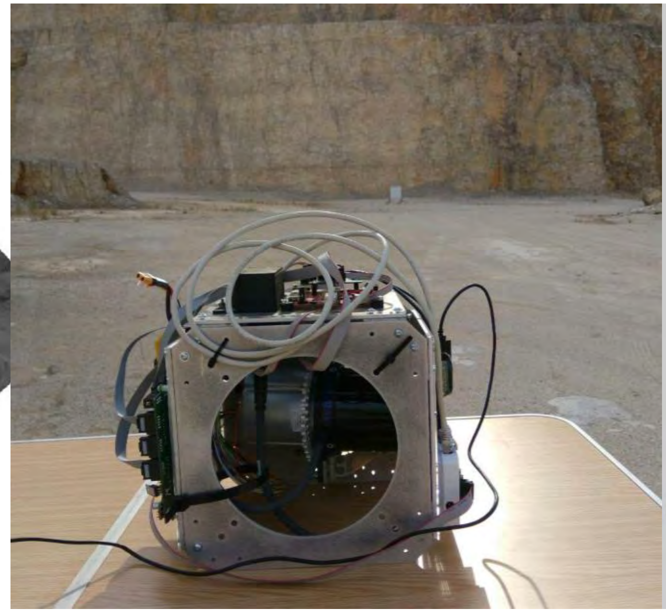



# Avionics Test Bench – Sensor verification tests completed

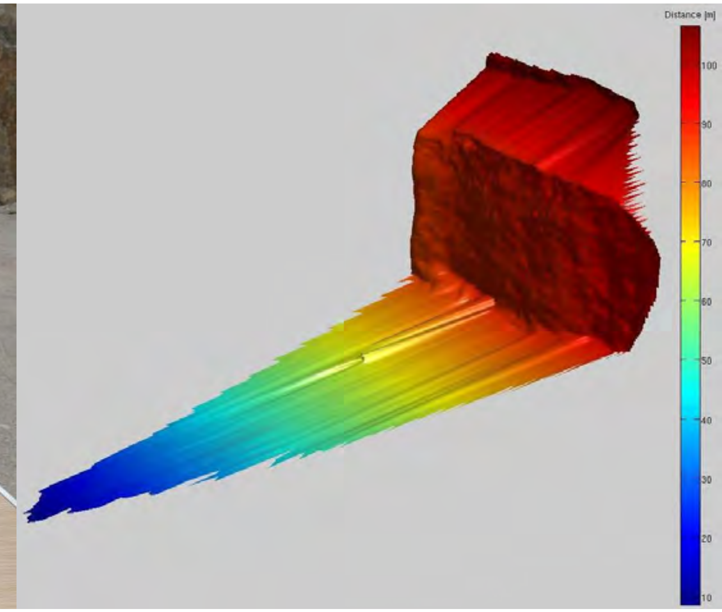
-All sensors integrated and verified to be working as expected

**Testing the Camera**



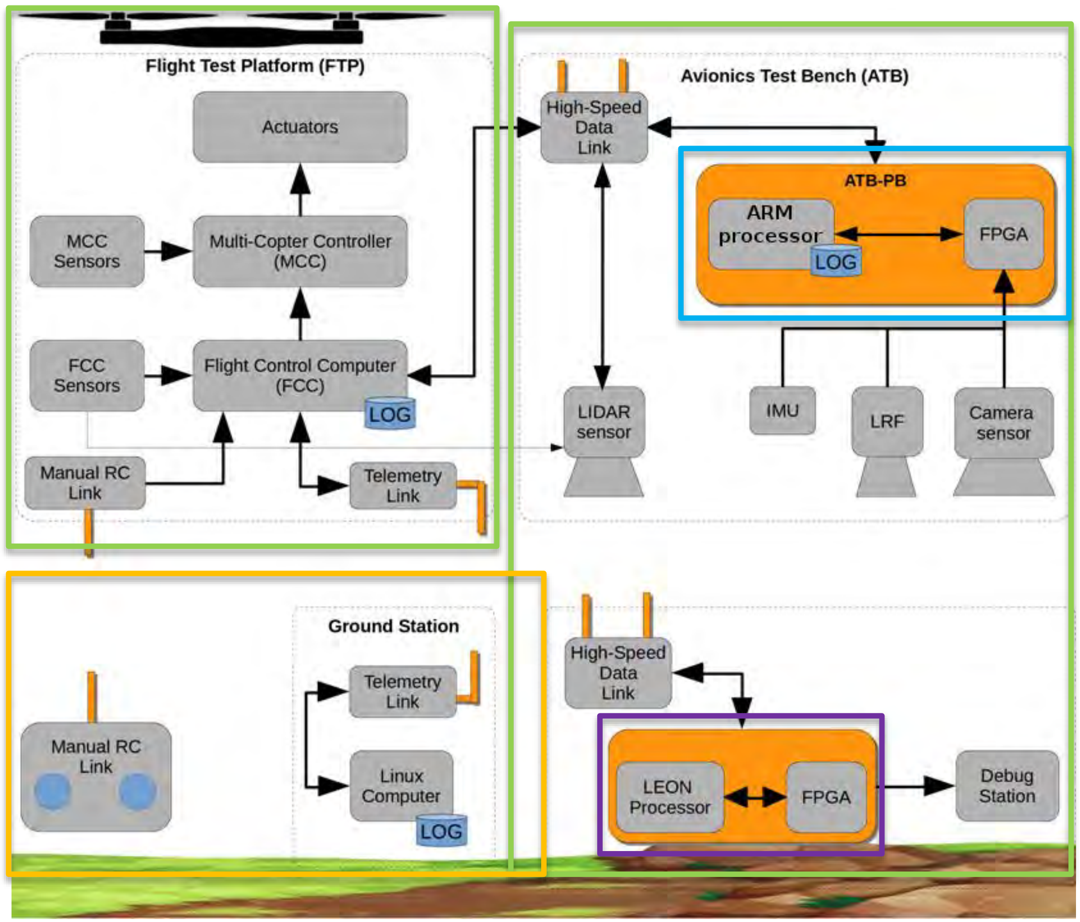


**Testing the LIDAR range**



# Flight Test configuration

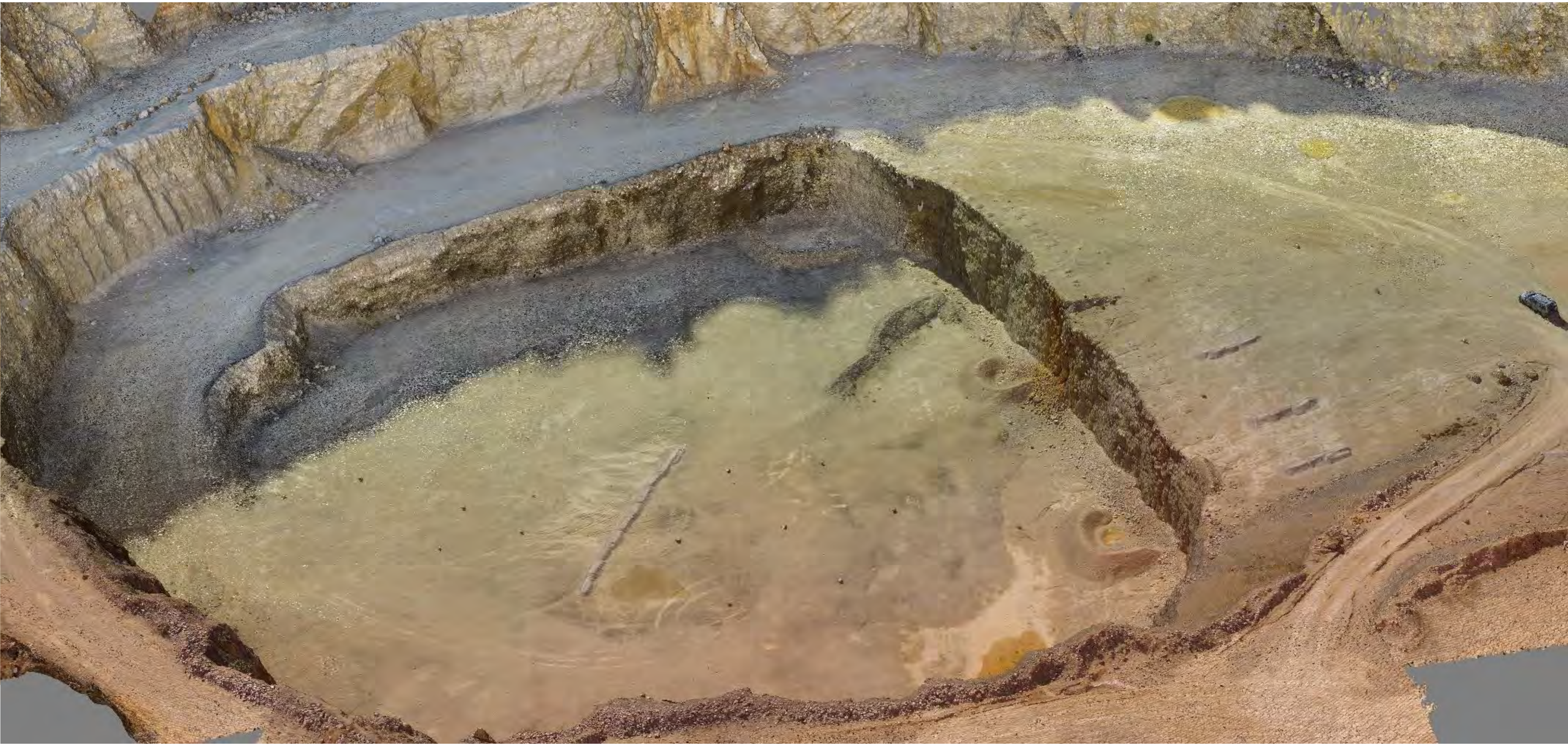
- Flight Segment
  - Flight Test Platform
  - Avionics Test Bench
- Ground Support Equipment
- Real-Time Software
  - VBN runs on-board
  - HDA runs on the ground



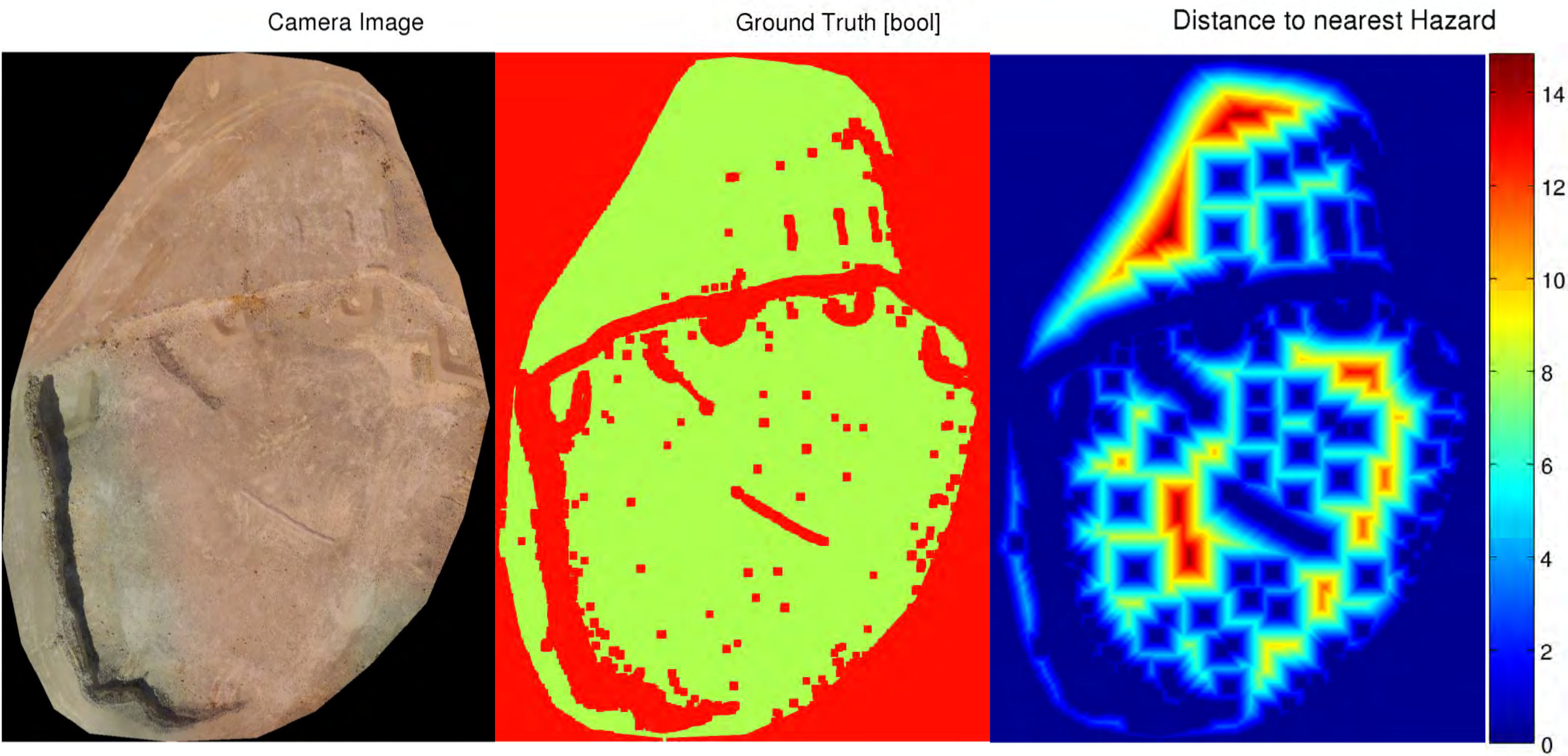
## Mars Representative Terrain

- -10,000 m$^2$ clean area (only dirt, no vegetation)
- -Natural soft & hard slopes
- -Limestone: sedimentary rock primarily composed of calcium carbonate in the form of the mineral calcite.
- -Clay;

## INTRODUCTION – Avoidance Algorithms Extended Development and Realistic Testing



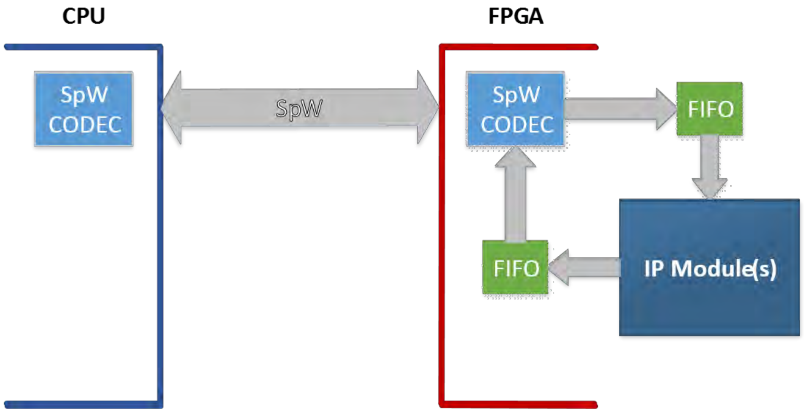
## INTRODUCTION – Avoidance Algorithms Extended Development and Realistic Testing



# H2DAS
# REAL-TIME SOFTWARE

## H2DAS Target System Specifications

- Specifically designed for space applications
- RTEMS real-time operating system
- CPU
  - SPARC V8 LEON2 soft-core
  - built-in IEEE-754 floating-point unit
  - maximum operating frequency of 72 MHz
- FPGA
  - ProAsic3E @ 18MHz
  - compatible with Microsemi's RTAX2000 radiation tolerant
- Interfaces
  - 4 SpaceWire
  - 2 CAN
  - 16 parallel I/O lines (8I+8O) and 6 GPIO lines
  - 2 UART interfaces for debug
- **CPU-FPGA communication is only possible via SpaceWire**



# Task Partitioning

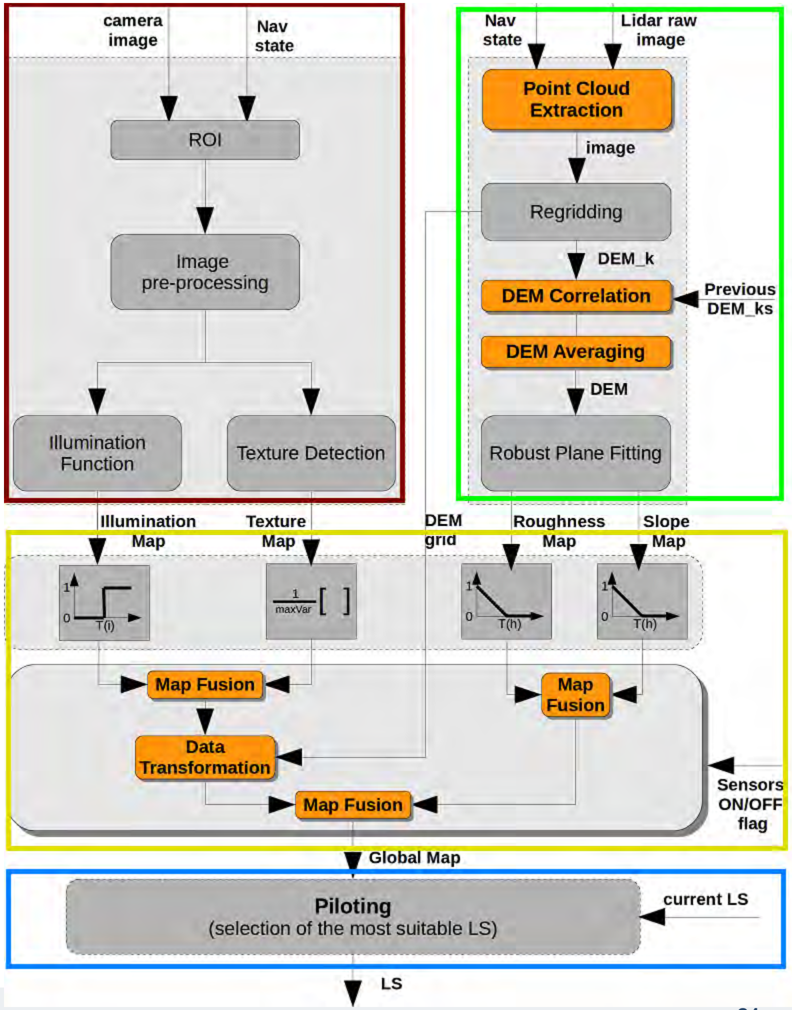
-4 computation tasks + 1 communication task

-Computation tasks are depicted in the diagram, as:

- -Camera Image Processing task
- -LIDAR Image Processing task
- -Map Fusion task
- -Piloting task

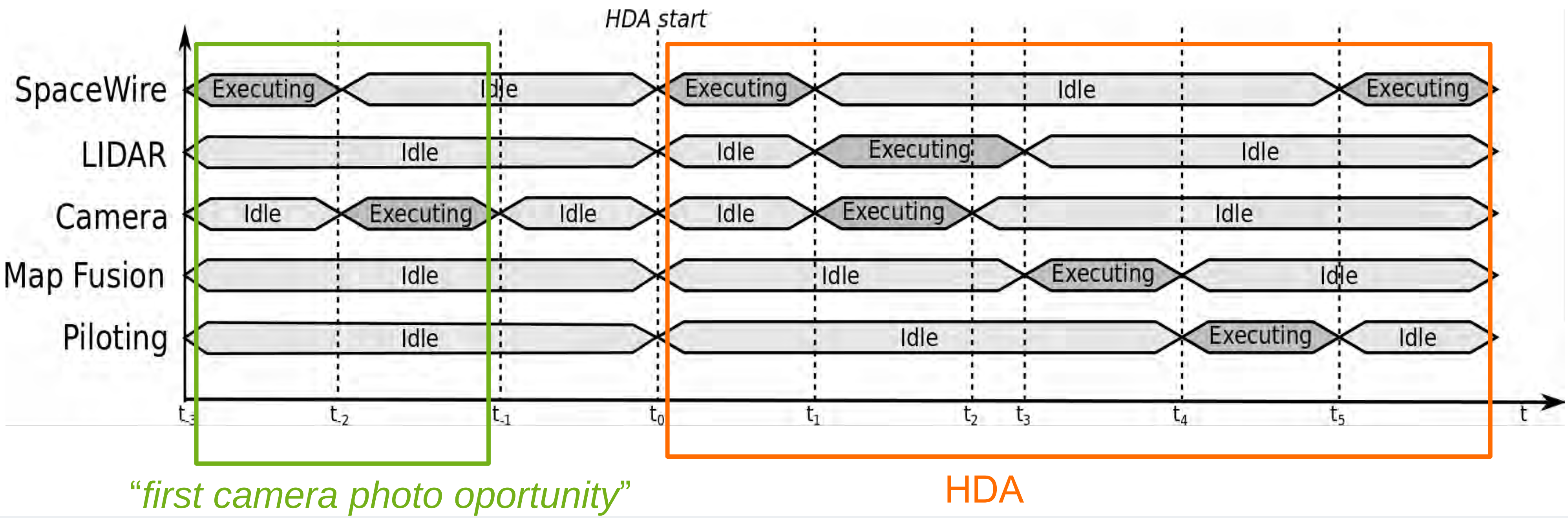
-Camera IP and LIDAR IP tasks can run in parallel

-Map Fusion and Piloting tasks ensure code modularity for testing other Map Fusion and Piloting algorithms



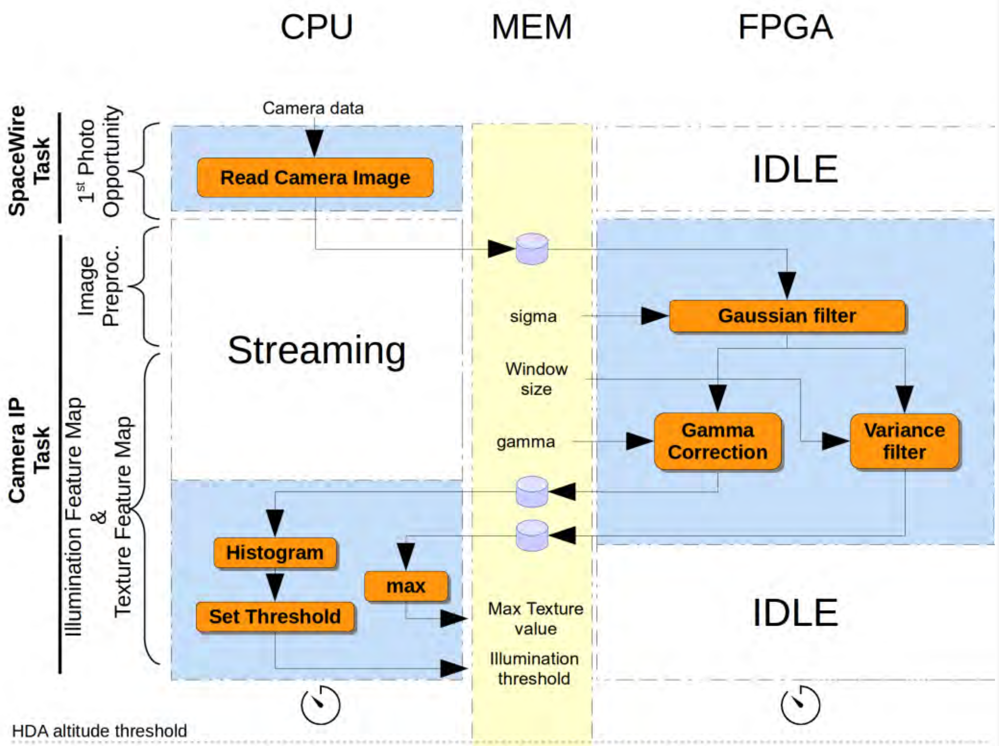
## Task Scheduling

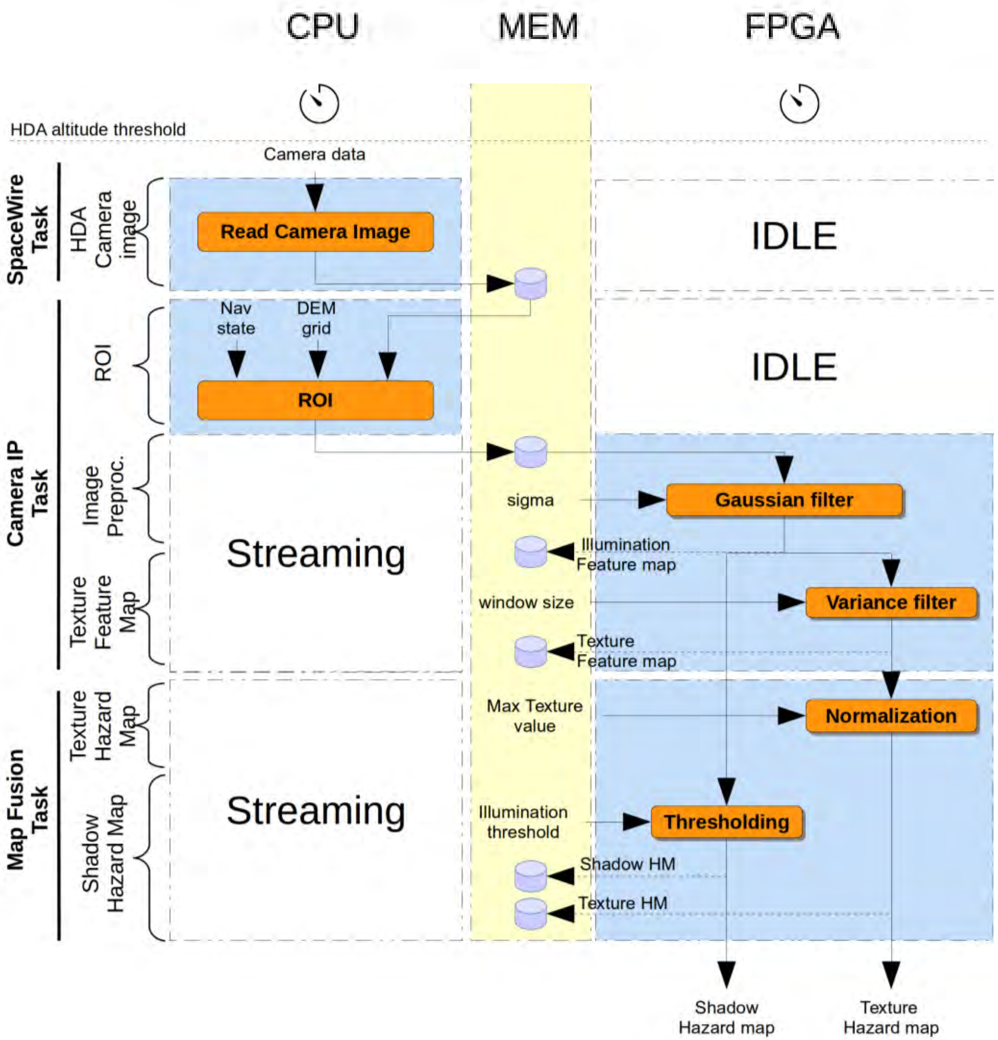
- The camera takes the “first photo opportunity” shortly before HDA is triggered
  - Allows for camera exposure calibration
  - Computes shadow threshold and variance normalization parameters
  - Enables hardware accelerated processing of the Camera IP as a single streamlined process



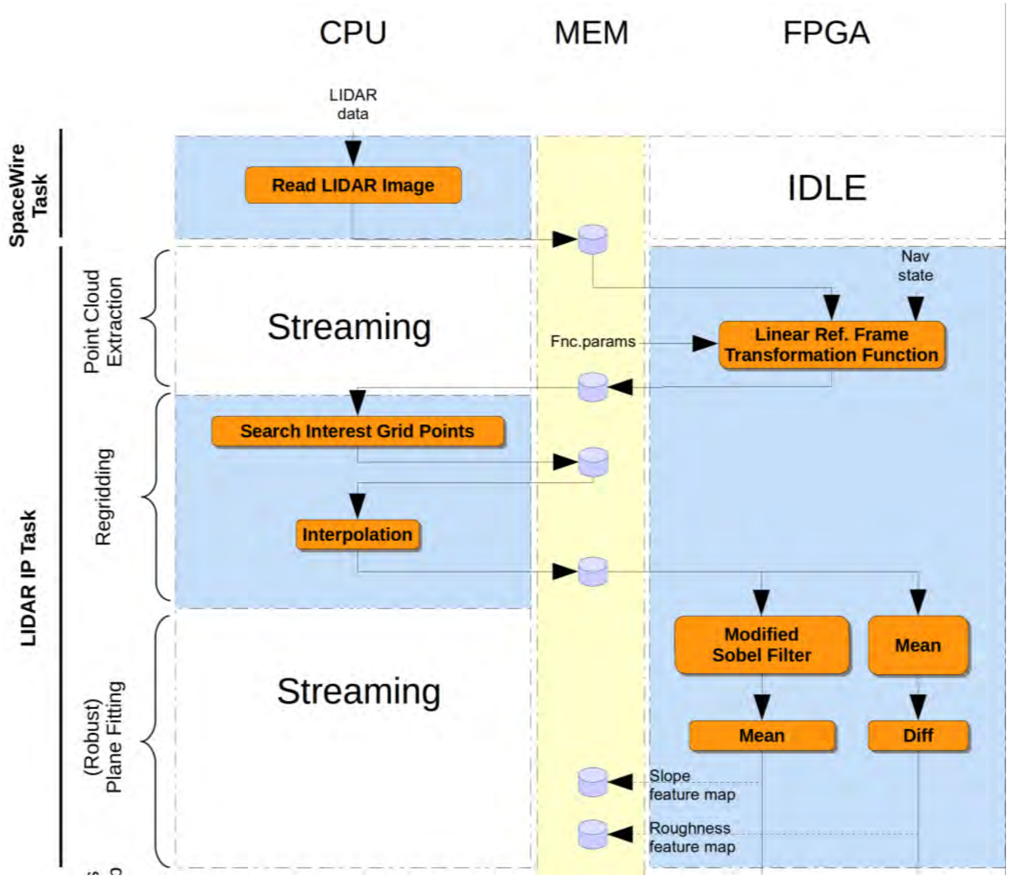
H2DAS RT SOFTWARE

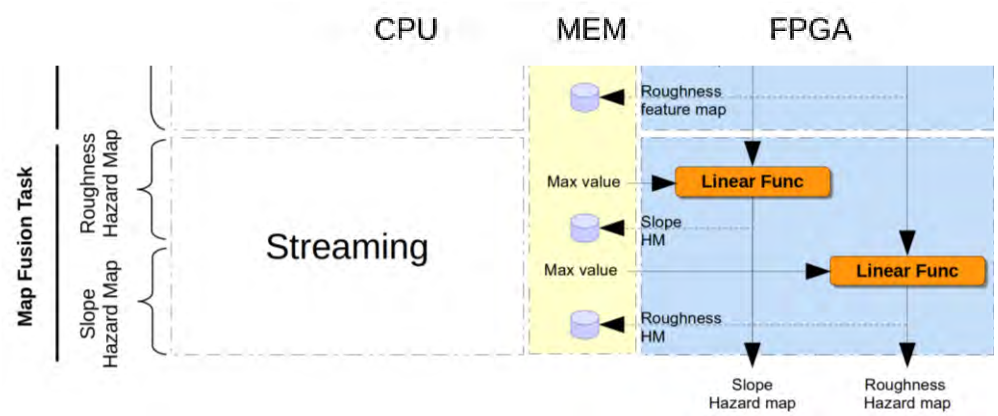
# Camera IP CPU/FPGA Partitioning



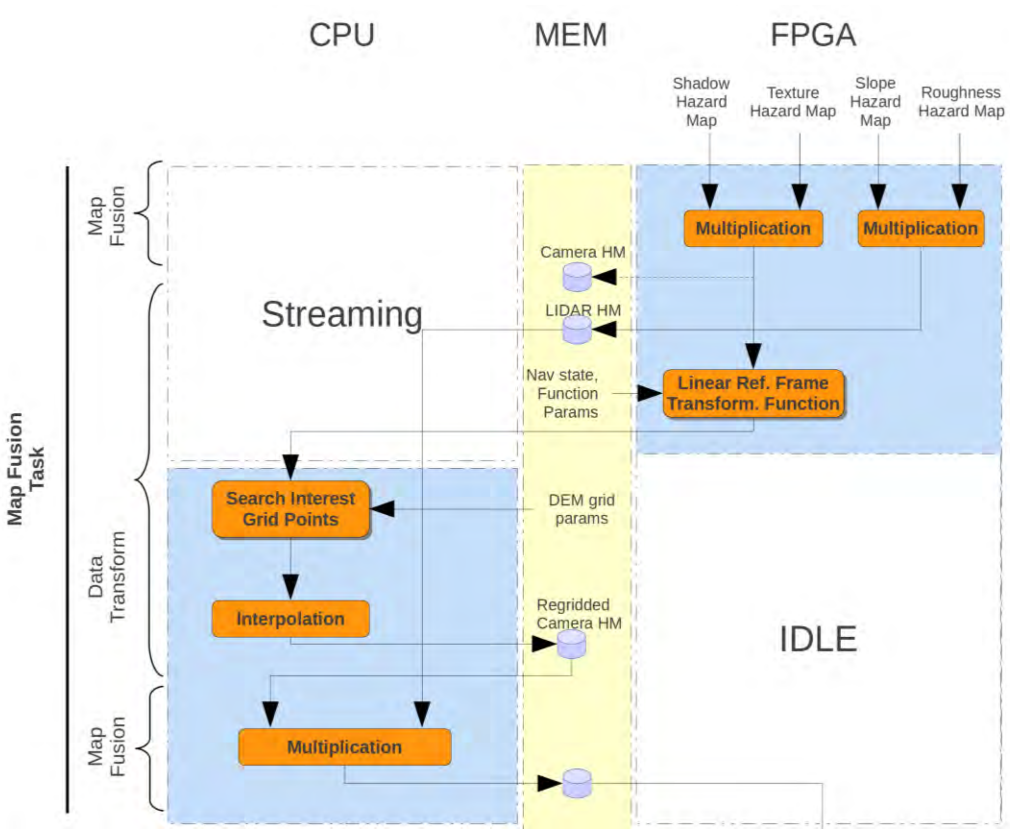



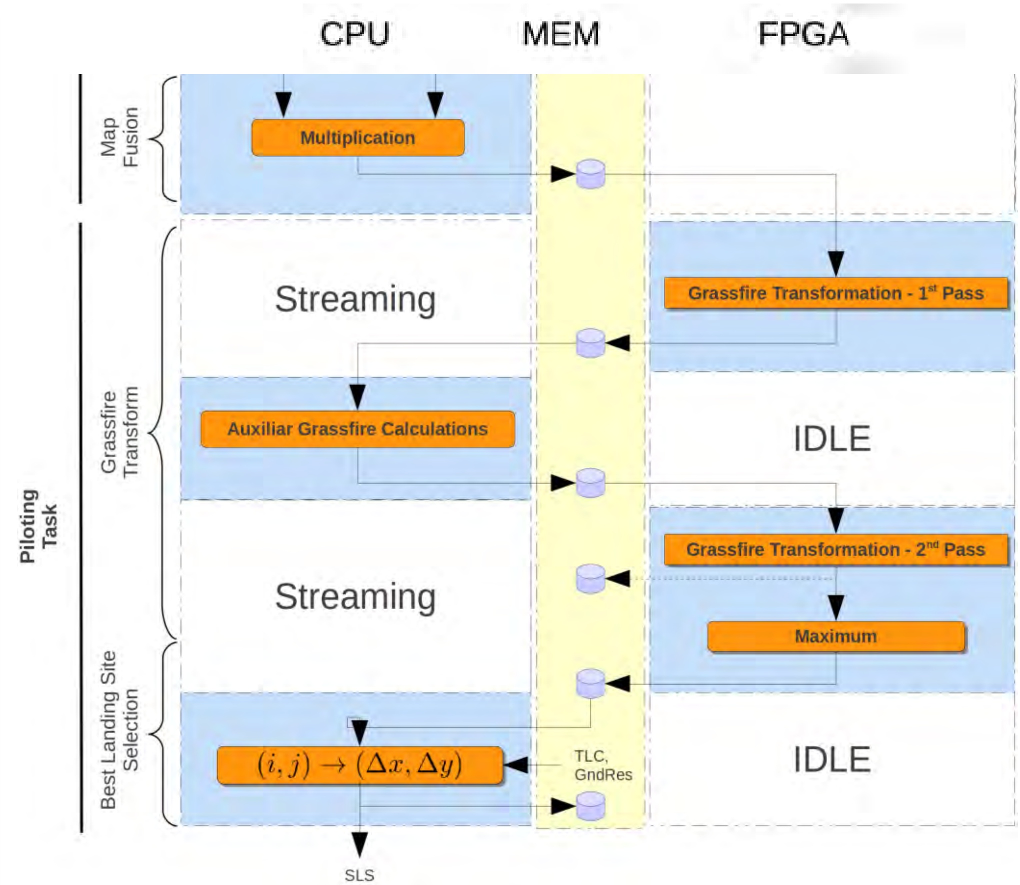
# LIDAR IP CPU/FPGA Partitioning



# Piloting CPU/FPGA Partitioning



## Hardware acceleration results

-Requirement of maximum 10 seconds to return retargeting command

-CPU-only execution time is already at 8sec

-CPU/FPGA partitioning overall speedup: x2

| Tasks | CPU-only Time elapsed (s) |
|---|---|
| **Camera IP** | 1.12 |
| **LIDAR IP** | 4.10 |
| **Map Merging** | 1.13 |
| **Compute HMs** | 0.47 |
| **Piloting** | 1.18 |
| **Total** | **8.00** |

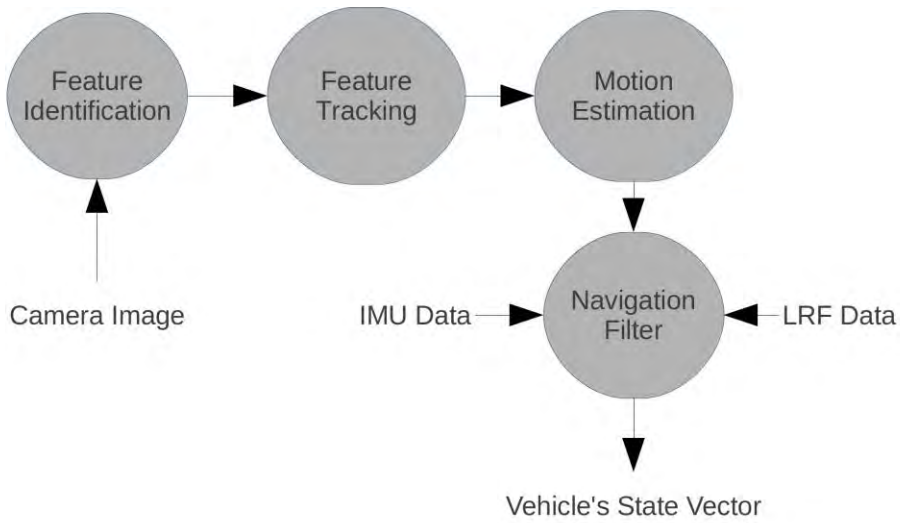
| | IP block | Core Cells | Block RAMs |
|---|---|---|---|
| | SpaceWire | 16% | 11% |
| H2DAS | LiDAR (min/max) | 50% | 23% |
| H2DAS | Camera | 35% | 16% |
| H2DAS | Piloting | 2% | 0% |
| H2DAS | **Total Utilization (%)** | **61400 (82%)** | **51 (46%)** |

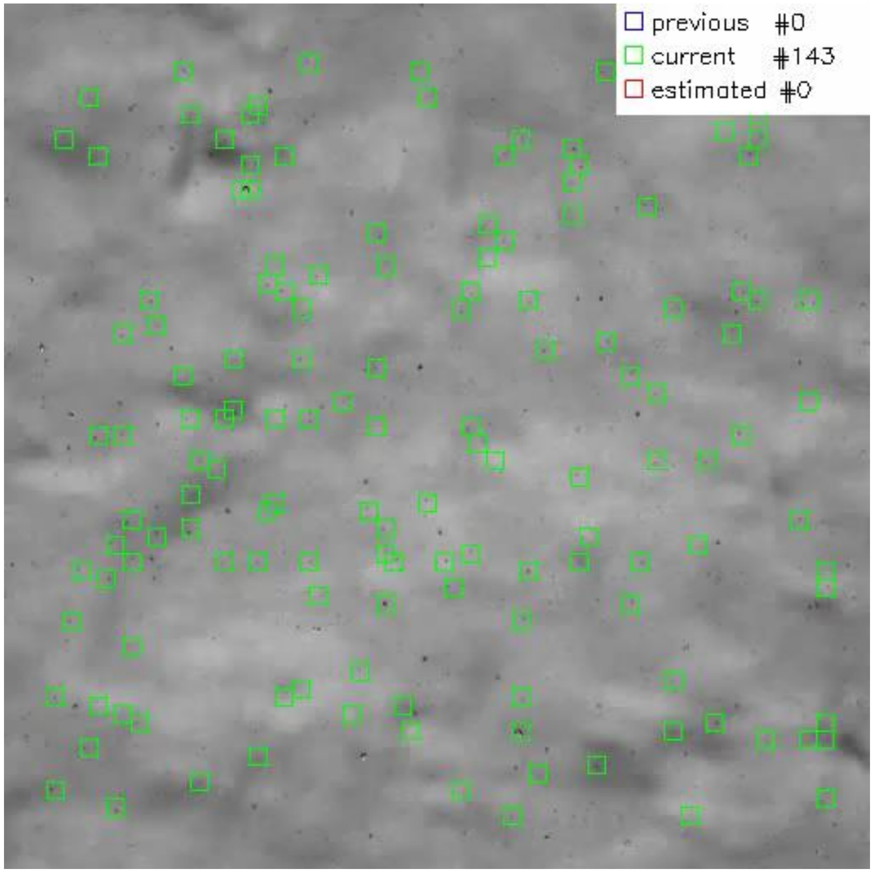
# VBN REAL-TIME SOFTWARE

## Vision Based Navigation (VBN)

**-Purpose:** Relative Navigation by tracking features and estimating motion between frames. Together with IMU and LRF data, estimate the vehicle's state vector.

**-Outputs:** Position, Velocity and Attitude

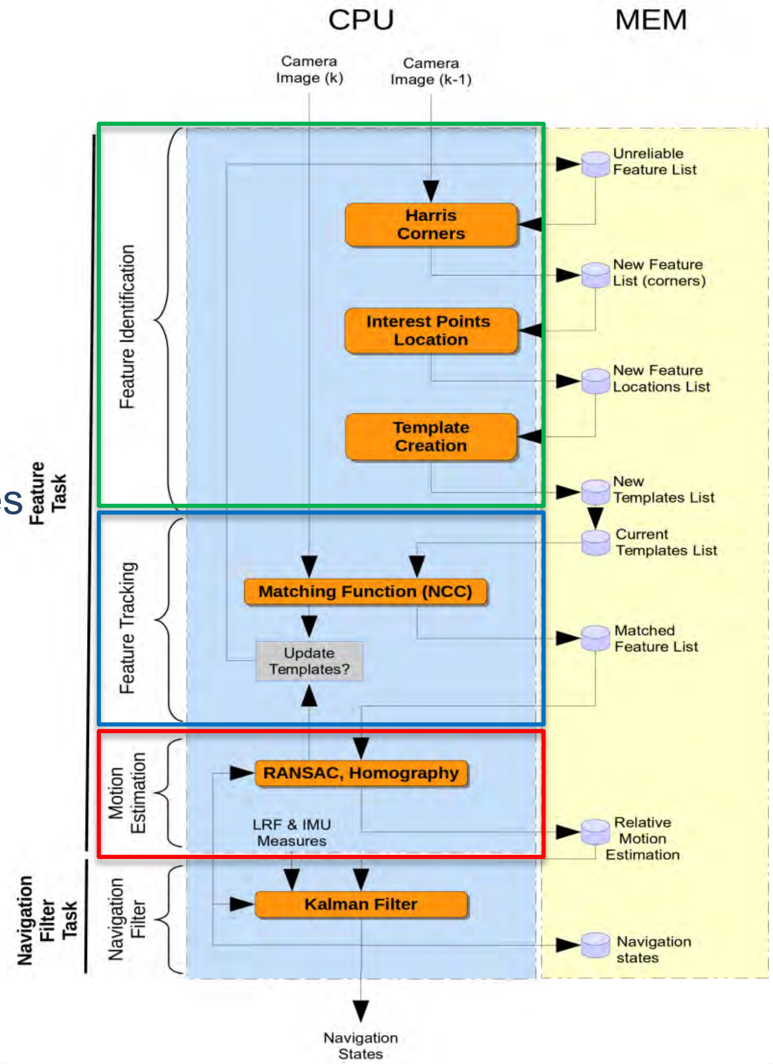


CPU-ONLY VISION BASED NAVIGATION

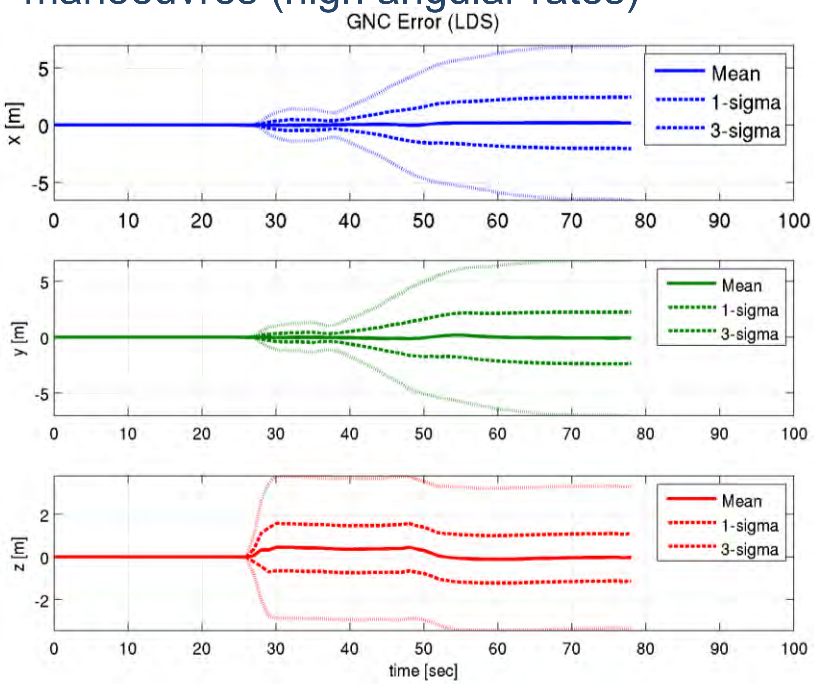
## VBN algorithm

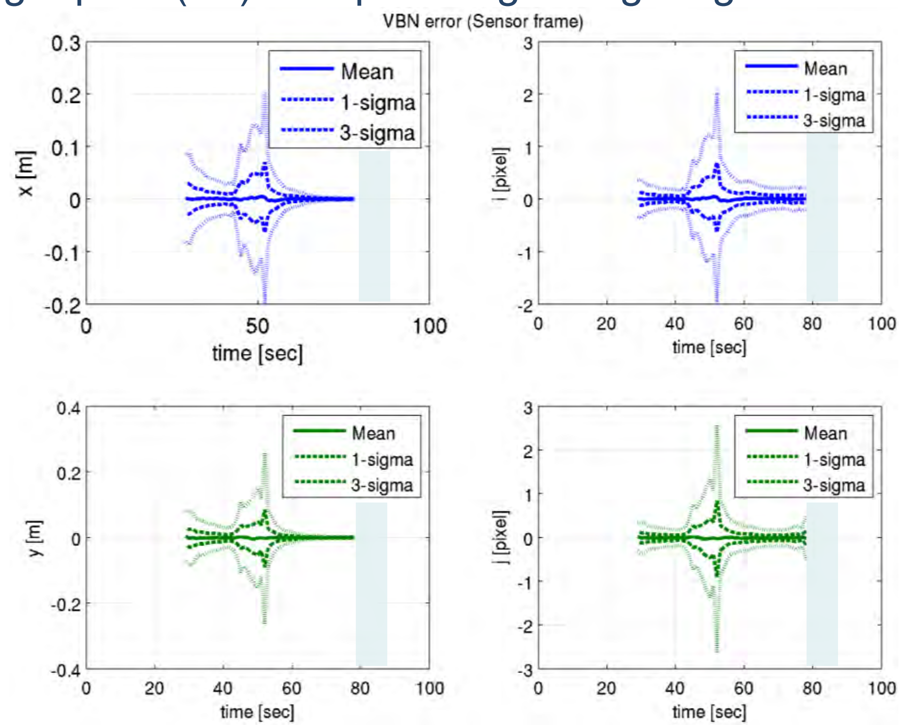
- **10Hz update rate**
- Feature identification
  - Run when valid features drop below 100
  - Keep old valid features
  - Harris corners => best 256 features
  - Max Euclidean distance => most disperse 150 features
  - Returns a list of 150 valid features
- Feature Tracking
  - Last feature position = New predicted position
  - Templates 11x11pix, Search Windows 51x51pix
  - Matching function = Normalized cross correlation
- Motion Estimation
  - Robust (RANSAC) Homography estimation
  - Use only horizontal and vertical image offset



# VBN Performance and GNC error

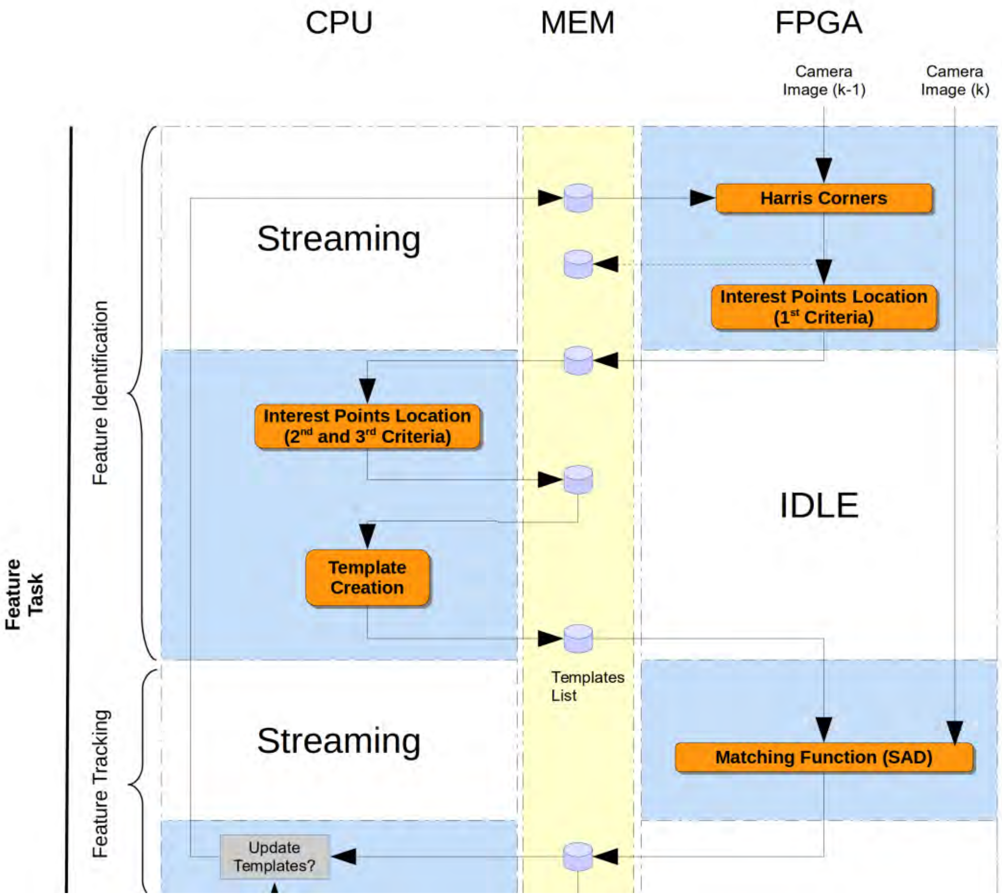
- 1200 Monte-Carlo simulations (MATLAB/Simulink 6DOF Dynamics w/ full GNC)
- Mean GNC error near zero, with ~5m dispersion (3σ), for both horizontal axes
- Visual observations' error dispersion not exceeding 1 pixel (3σ) except during retargeting manoeuvres (high angular rates)

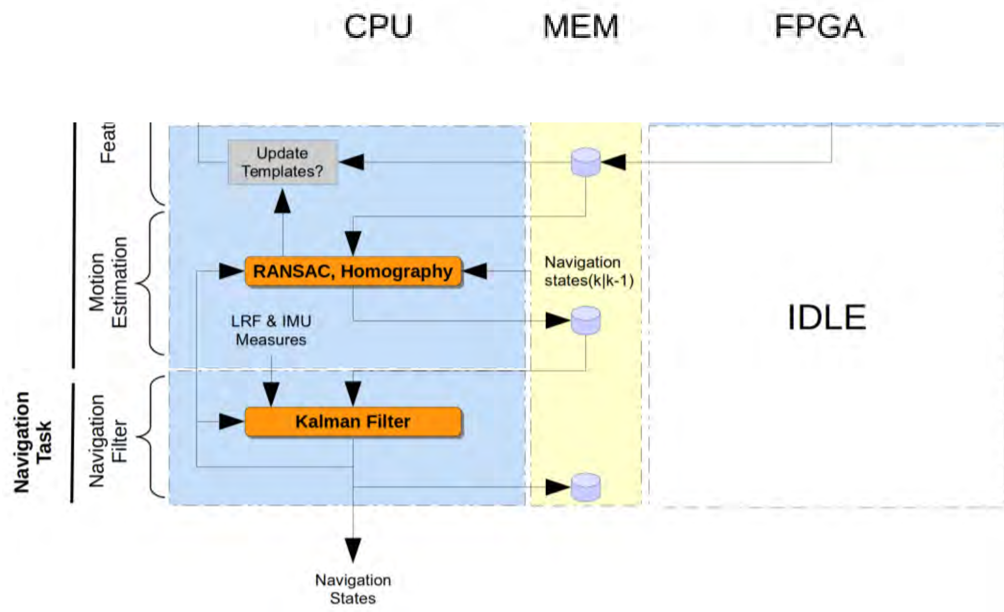


CPU+FPGA VISION BASED NAVIGATION

# VBN CPU/FPGA Partitioning

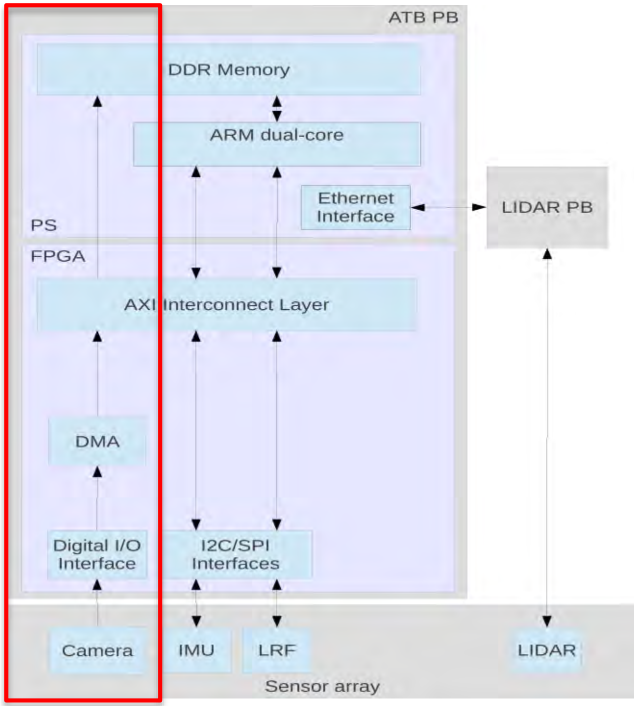


# Target System Specifications

## -Zedboard

- ARM Cortex-A9 hard-core CPU @ 665MHz
- Zynq-7020 FPGA (from Artix family) @ 66MHz




| Characteristic | Value |
| --- | --- |
| Number of GPIO pins | 40 |
| Voltage of GPIO pins | 3.3V |
| Zynq Model | Z7020 |
| Debug Facilities | Good |
| Community Support | Good |
| Size | 160x135x25mm |
| Weight | ~200gr |
| Price | 495$ |

# Hardware acceleration – FPGA Fitting Results

-VBN module fits comfortably within the available FPGA resources

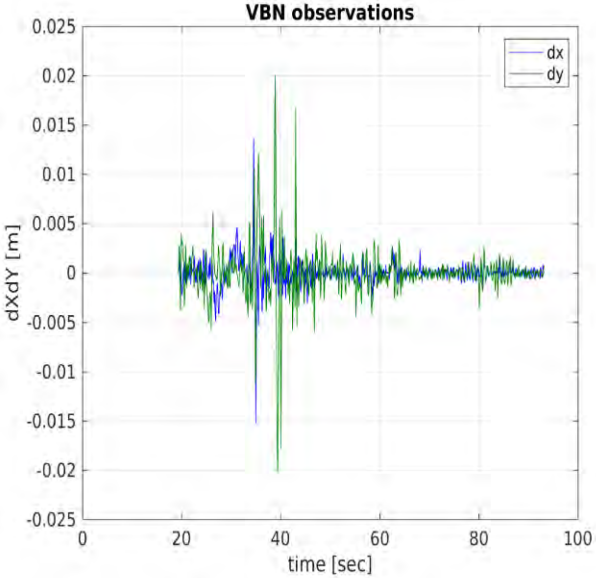
| | IP block | Slices | LUTs | FF pairs | BRAM Tiles | DSPs |
|---|---|---|---|---|---|---|
| **Feature Identification** | AXI Harris Controller | 63 | 125 | 85 | 0 | 0 |
| | Determinant computation | 133 | 170 | 82 | 0 | 3 |
| | Gaussian filters 7x7 | 1175 | 3003 | 918 | 4.5 | 30 |
| | Gradient computation | 155 | 294 | 109 | 3 | 0 |
| | Harris Maximum selector | 5257 | 19257 | 8473 | 0 | 0 |
| | Custom Multipliers | 121 | 309 | 61 | 0 | 0 |
| **Feature Tracking** | AXI template controller | 78 | 175 | 89 | 0 | 1 |
| | Main Track Features IP | 1072 | 2784 | 2218 | 0 | 0 |
| **Total Utilization (%)** | | **8 054 (60.5%)** | **26 117 (49.1%)** | **12 035 (22.6%)** | **7.5 (5.3%)** | **34 (15.5%)** |

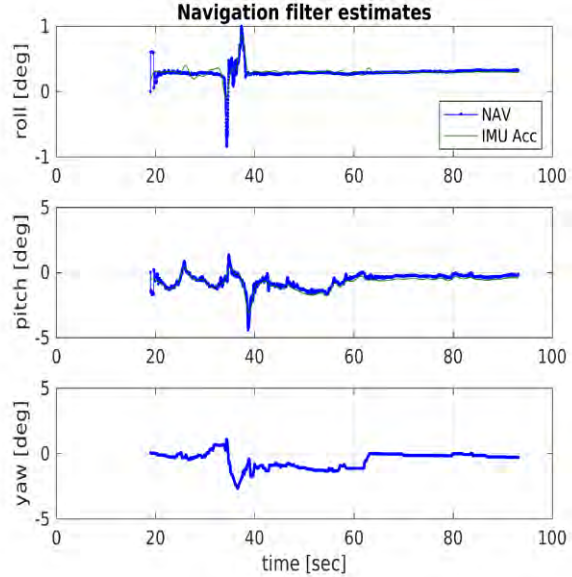
RESULTS

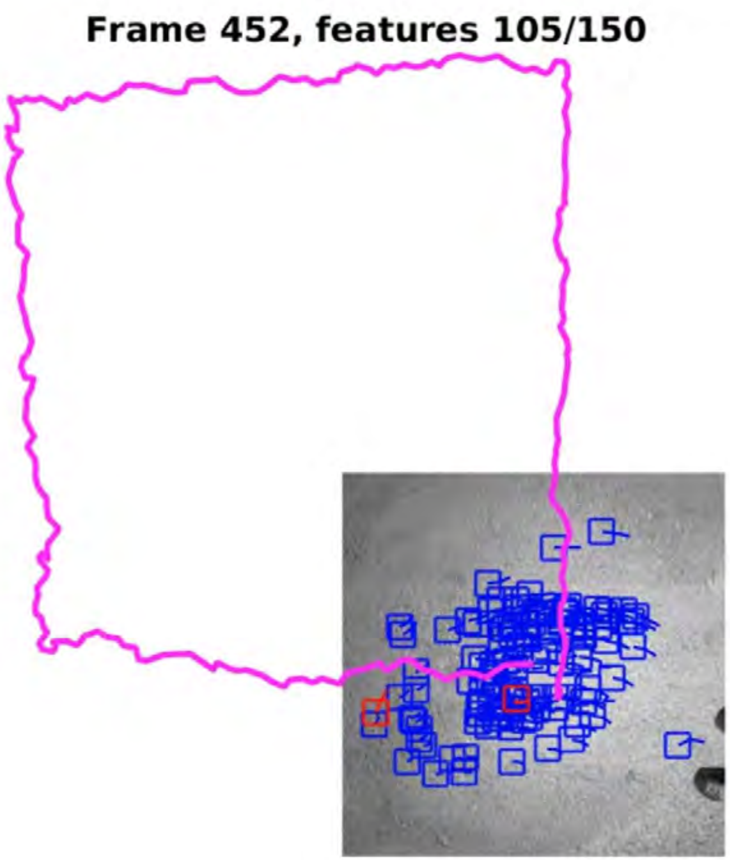
## VBN Results

-Example of Navigation plots from actual data

-Walking a square path of 4x4 m



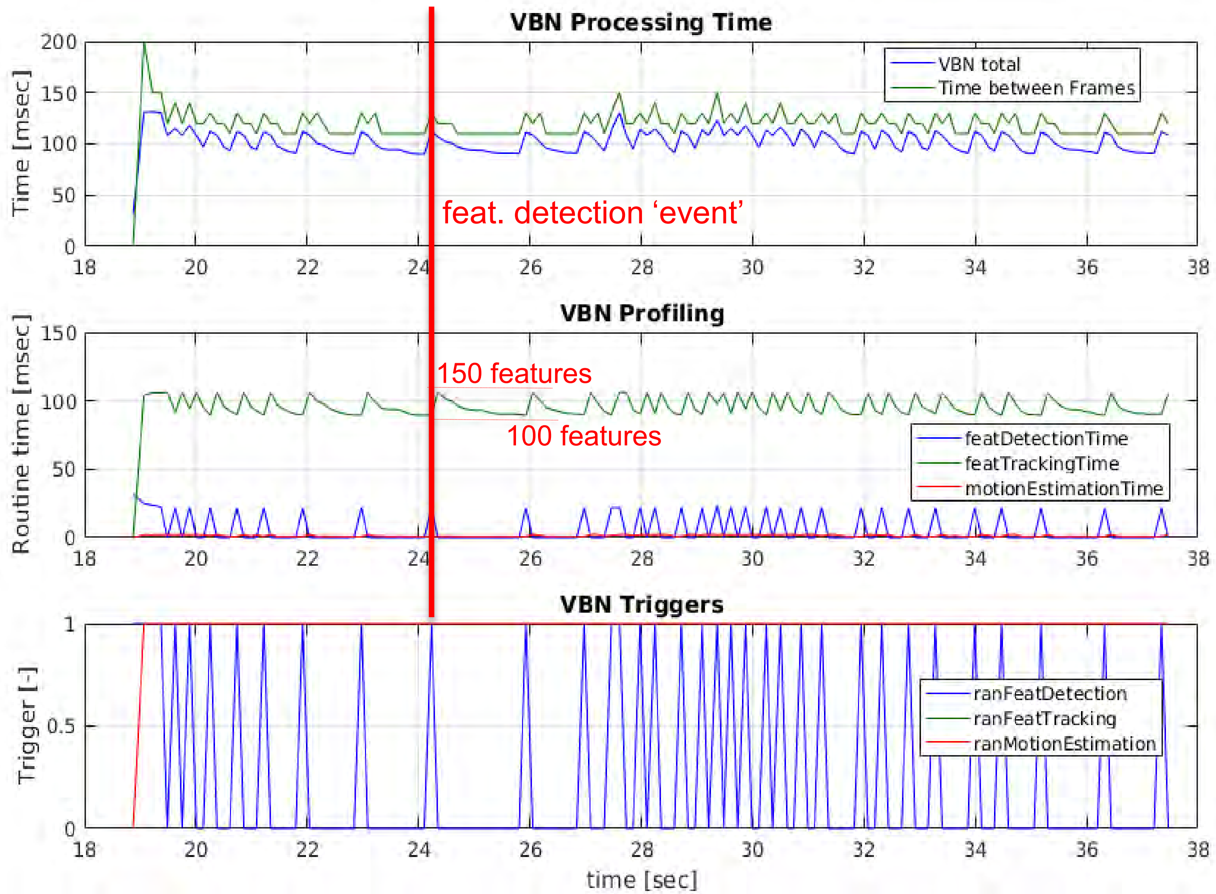



**RESULTS**

# VBN Results - VBN Task refresh rate breakdown

- -VBN
  - -Target design rate = 10Hz
  - -Current average rate = 8.4Hz
- -Feature Detection
  - -20msec execution time
  - -Avg rate = 16%*10Hz
- -Feature Tracking
  - -Min 90msec @ 100 features
  - -Max 110msec @ 150 features
  - -Should run at 10Hz
- -Motion Estimation
  - -Less than 1msec execution time
  - -Runs at 100Hz



## Flight Testing

- The Flight Tests will comprise a Monte Carlo Test campaign of a total of 500 flights
- Several factors have been delaying and postponing the Flight Test campaigns
  - A crash attributed to bad static pressure readings in the 3rd party closed-source multi-copter controller
  - An exceptionally long winter

## Concluding Remarks

- The proposed $H^2DAS$ algorithm has been tested in simulation environment with a Monte Carlo campaign of 1800 test cases
- The results verify the requirement "The $H^2DAS$ system shall have a probability of safe site selection > 99%" with a confidence level of 99.9%
- $H^2DAS$ real-time software is fully compliant with the requirement of returning a retargeting decision in under 10 seconds after HDA is triggered

- The proposed VBN algorithm has been tested in simulation environment with a Monte Carlo campaign of 1200 test cases
- The results show unbiased GNC error with ~5m dispersion ($3\sigma$) radius on the horizontal plane
- VBN real-time software is working at 8.4Hz. Reducing 15% the number of tracked features will meet the design 10Hz frame update

- Flight Test campaigns ongoing, results not yet available
- VN&HDA algorithm performance degradation and impact on the navigation accuracy will be evaluated based on actual flight test data

# THANKS

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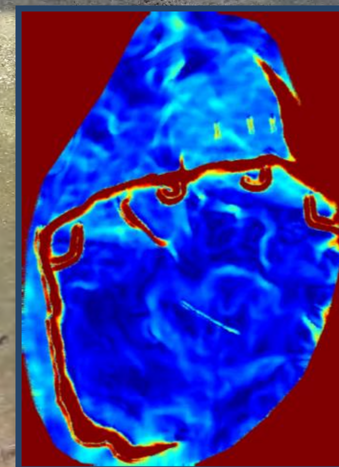

**Slope Map**

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  - Sensor Data Fusion for Hazard Mapping and Piloting (FUSION)
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- The view expressed in this publication can in no way be taken to reflect the official opinion of the European Space Agency