Terrain Relative Navigation Performance in Mars 2020

IPPW 2016


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LVS is powered on shortly after Cruise Stage Separation

Nav Filter (NF) converges with TDS measurements and begins providing NF estimates to LVS
- **time varies**

**LVS initialization**
- **6 seconds**
  - Baseline: 3.7 km AGL (Between 3.0 km & 3.7 km AGL)

First LVS **reduced** performance solution available
- **4 seconds**
  - Accuracy: 54 m, 99%-tile, per solution
  - Robustness: Provide solutions 95% of the time

First LVS **full** performance solution available
- **time varies**
  - Baseline: 2.15 km AGL (Between 1.6 km & 2.3 km AGL)
  - Accuracy: 40 m, 99%-tile, per solution
  - Robustness: Provide solutions 99% of the time
  - LVS continues to provide solutions (as low as BSS or 2.0 km AGL)

Safe Target Selection begins
- **~2.6 seconds**
  - Performance calculated at 2.3 km

Safe target selected and provided to MSL-heritage powered approach
- Divert maneuver is executed

*If TRN ceases to function at any point, we execute a MSL-heritage backshell avoidance divert by default*
LVS Architecture

LVS operates during parachute descent when descent stage and rover are attached and inside backshell.

Descent Stage

LVS uses the Descent IMU (DIMU) on the descent stage.

Rover

LVS camera (LCAM) is on rover, 90° FOV.

The VCE is inside the rover.
Deriving the needed TRN capability

A. Max landing hazard size, diameter = 200m
B. Necessary safe zone around the hazard of 120m
C. Capable divert errors of radius = 60m (diameter = 120m), based on available fuel
D. Safe target reachable region of radius = 167.5m (diameter = 335m)

Target Line: Need to be able to reach this to meet A – C

S/C required to reach this region. Includes 15m margin over Target line.
TRN Error Budget – Allocations

TRN Performance
Req: 60 m, 99%
Allocation: 49.8 m, 99%

25% Reserved margin on new,
5% Reserved margin on heritage

Targeting Error
Allocation: 42.5 m, 99%

Knowledge Error
Allocation: 24.75 m, 99%

Control Error
Allocation: 3 m, 99%

LVS Localization
Allocation: 40 m, 99%

LVS & EDLGNC state
synchronization
Allocation: 2.83 m, 99%

Map Co-Registration
between LVS and STS Map
Allocation: 6 m, 99%

LVS Map Accuracy
Allocation: 12 m, 99%
LVS Localization Performance

- LVS Localization error = Image estimation error + DIMU propagation error between image updates = \textbf{23.71 m, 99%}
- Image estimation error = 19.9m @ 2300m
  - Max across off-nadir angle operational envelope
  - Conservative single image only estimation assessment
- DIMU Propagation error = 3.78m after 1s
  - Includes velocity error and accel bias effect on localization estimate
  - Includes effect of DIMU alignment errors and timing errors on localization

![Graph of LVS Localization Performance](image-url)

- Increasing angular separation of landmarks
- Decreasing number of landmarks

![Legend of Graph](image-url)

- Operational Envelope
LVS & EDLGNC state synchronization

- State synchronization error = \(2.50\, \text{m}, \, 99\%\)
  - RSS of Time synchronization and Frame sync.

- Time synchronization
  - \(T_{\text{LVS}}\) = LVS solution time
  - \(T_{\text{NF}}\) = EDLGNC Navigation Filter estimated state closest in time to LVS solution
  - Error = Max Velocity \* Max Time = 1.72m
    - Max Time = \(T_{\text{NF}} - T_{\text{LVS}}\) = 0.0156s (64 Hz RTI)
    - Max Velocity = 110 m/s

- Frame synchronization
  - LVS solution in LVS Map frame
  - EDLGNC Navigation Filter solution in Mars Surface Frame (MSF)
  - Error from Nav Filter error at MSF instantiation = 1.81m
    - East/Up \(\rightarrow\) 3m Nav Filter position error
    - North \(\rightarrow\) Attitude error \(\approx\) 0.15 deg
Map Co-Registration & Accuracy

LVS Map
From CTX images
6m per pixel

STS Map
From HiRise images
1m per pixel

Map Co-Registration Max = 1 CTX Pixel
Map Co-Registration = **6m, 99%**

Map Accuracy caused by distortion between Map and Truth
Map Accuracy = **12m, 99%**
TRN Error Budget – Summary

TRN Performance
Req: 60 m, 99%
CBE: 31.28 m, 99%

48% Margin to Requirement

Targeting Error
Allocation: 42.5 m, 99%
CBE: 27.36 m, 99%

Knowledge Error
Allocation: 24.75 m, 99%
CBE: 15.16 m, 99%

Control Error
Allocation: 3 m, 99%
CBE: 0.47 m, 99%

LVS Localization
Allocation: 40 m, 99%
CBE: 23.71 m, 99%

LVS & EDLGNC state synchronization
Allocation: 2.83 m, 99%
CBE: 2.50 m, 99%

Map Co-Registration between LVS and STS Map
Allocation: 6 m, 99%
CBE: 6 m, 99%

LVS Map Accuracy
Allocation: 12 m, 99%
CBE: 12 m, 99%

• TRN error budget constructed based on nominal M2020 use
• Appropriate margins reserved on new items versus heritage elements
• System shows healthy margins to requirements
TRN Operational Envelope

Horizontal Velocity = +/- 70 m/s radially

Vertical Velocity = 60 m/s to +115 m/s

Attitude Rates <= +/- 50 °/s

Atmospheric Dust Tau < 1.5

Sun elevation = 25deg to 55deg
Sun azimuth = 240 to 310 deg (clockwise from N)
Sun distance <= 1.58 Au

Off Nadir Angle <= 45°

Terrain elevation changes < 150m 99%-tile over a 1500m x 1500m patch
Terrain slopes < 15 deg (calculated as a plane fit to a 1500 m x1500m patch)
LVS Error Budget – Allocations

CBEs described in detail under appropriate design subsections

LVS Localization
Allocation: 40 m, 99%

LVS IMU-based Propagation between images
Allocation: 4 m, 99%

13.5% Reserved Margin

LVS Image-based Localization
Allocation: 30.59 m, 99%

RSS

Position error due to image correlation
Allocation: 27 m, 99%

Position error due to camera calibration error
Allocation: 5 m, 99%

Position error due to static misalignments
Allocation: 1 m, 99%

Position error due to Map elevation error
Allocation: 6 m, 99%

Position error due to local Map distortion
Allocation: 12 m, 99%

Position error due to LCAM/DIMU latency
Allocation: 1 m, 99%
LVS Error Budget – CBEs

CBEs computed at
- **2300m**, 45 deg off-nadir angle,
- 0.27 deg alignment knowledge error
- 1 pixel camera calibration noise

40.7% Margin to Requirement

\[ \text{RSS} \]

LVS Localization
Allocation: 40 m, 99%
CBE: 23.71 m, 99%

\[ \text{LVS Image-based Localization} \]
Allocation: 30.59 m, 99%
CBE: 19.93 m, 99%

\[ \text{LVS IMU-based Propagation between images} \]
Allocation: 4 m, 99%
CBE: 3.78 m, 99%

Position error due to
image correlation
Allocation: 27 m, 99%
CBE: 18.15 m, 99%

Position error due to
camera calibration error
Allocation: 5 m, 99%
CBE: 3.30 m, 99%

Position error due to
static misalignments
Allocation: 1 m, 99%
CBE: 0.005 m, 99%

Position error due to
Map elevation error
Allocation: 6 m, 99%
CBE: 2.278 m, 99%

Position error due to
local Map distortion
Allocation: 12 m, 99%
CBE: 5.38 m, 99%

Position error due to
LCAM/DIMU latency
Allocation: 1 m, 99%
CBE: 0.002 m, 99%

CBEs described in detail under appropriate design subsections
LVS Error Budget – CBEs, Max

CBEs computed at
- **3100m**
- 3.7km max init + 10s req * (60m/s, min vel)
- 45 deg off-nadir angle,
- 0.27 deg alignment knowledge error
- 1 pixel camera calibration noise

**19.3% Margin to Requirement**

LVS Localization
Allocation: 40 m, 99%
CBE: 32.27 m, 99%

LVS IMU-based Propagation between images
Allocation: 4 m, 99%
CBE: 3.78 m, 99%

CBEs described in detail under appropriate design subsections

**RSS**

Position error due to image correlation
Allocation: 27 m, 99%
CBE: 26.52 m, 99%

Position error due to camera calibration error
Allocation: 5 m, 99%
CBE: 4.51 m, 99%

Position error due to static misalignments
Allocation: 1 m, 99%
CBE: 0.005 m, 99%

Position error due to Map elevation error
Allocation: 6 m, 99%
CBE: 2.78 m, 99%

Position error due to local Map distortion
Allocation: 12 m, 99%
CBE: 7.5 m, 99%

Position error due to LCAM/DIMU latency
Allocation: 1 m, 99%
CBE: 0.002 m, 99%