POLITECNICO
MILANO 1863

Analysis and validation of spaceborne synthetic imagery using a Vision-Based pose initialization algorithm for non-cooperative spacecrafts

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D-ORBIT
NEW SPACE SOLUTIONS

Introduction

Table of contents

Aim of the thesis → Develop a data-set of images representative of in-orbit real operative conditions and test them using a Computer Vision (CV) algorithm.

Nowadays, different classes of missions envision a major role for close-range proximity operations

Purposes:

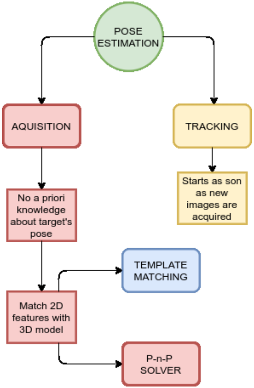
- Formation Flying (FF);
- On-Orbit Servicing (OOS);
- Active Debris Removal (ADR).

The main challenge when performing close-range operations in OOS and ADR missions is when the target S/C may be uncooperative (no markers or other specific supportive means). Thus, when operating in close-proximity the time evolution of the target's pose must be estimated in autonomy by exploiting the sensors available on the S/C actively performing the servicing maneuvers.

Monocular Solution

Requirements

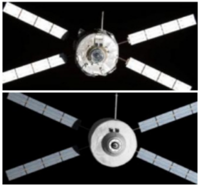
- Target 3D model availability
- On-Board real-time execution
- Robustness to illumination
- Robustness to background
- Robustness to variability of pose



$\longrightarrow$ Need a representative data-set to develop complex CV algorithms

Synthetic Image Generation: commercial solutions

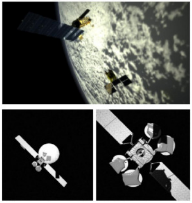
ESA PANGU



Need to be ESA project contractor

- OpenGL image rendering
- Can make use of GPU cores
- Closed-Source

Airbus SurRender

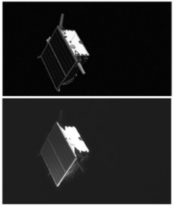


Need to buy a license from Airbus

- Ray tracing image rendering
- Fully parallelized
- Closed-Source

Synthetic Image Generation: academical solutions

SPEED DATA-SET



Only the Tango S/C is represented in the images.

- TRON facility for real images
- OpenGL image rendering
- Closed-Source

URSO DATA-SET

Lack of photometric accuracy

- Implemented using Unreal Engine 4
- Developed to train neural networks
- Open-Source rendering engine

Synthetic Image Generation

Requirements

→ Emerges the need for a tool capable of rendering images for CV algorithms training which must:

- be affordable for small research center or small companies
- be capable of rendering different kinds S/C
- be able to accomodate solar-system sized scenes
- be able to also render composite background

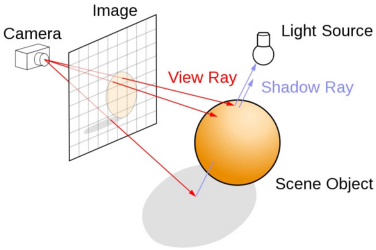
→ The images have to be representative of a real data-set taken by a true camera!

→ A lack of realism can lead to wrong assumptions and thus incoherent results!!!

Ray Tracing

POV-Ray represents a viable solution

- Support **mesh** and objects
- Customizable optical properties
- Customizable light properties
- Customizable textures support
- Customizable camera parameters
- Used by ESA before PANGU



→ It simulates the physics of light!

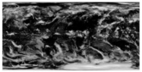
→ Noise can be modeled and added *a posteriori* to enhance fidelity.

Earth Modeling

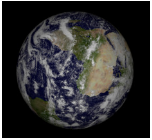
→ Use three different layers to differentiate optical parameters and textures for seasonality variations

Terrain

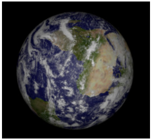
Landmask



Clouds



Same optical parameters

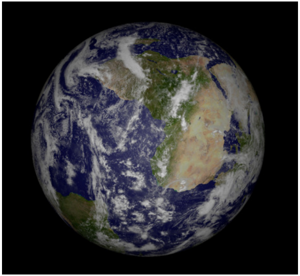


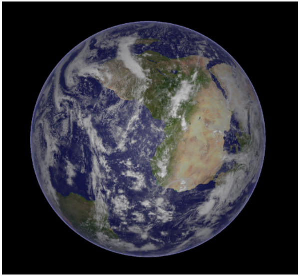
Different optical paramters

→ The Sun has been modeled using POV-Ray **area_light** feature

Earth Modeling

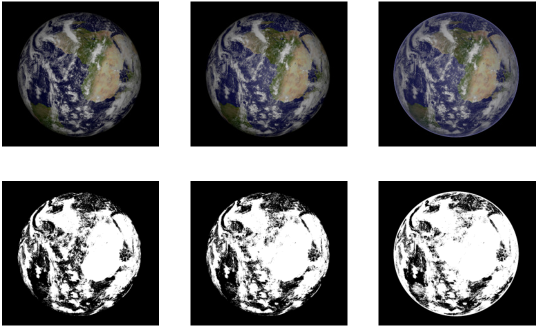
→ Add 25 km thick atmosphere augment realness and challenge edge detection CV algorithms


No atmosphere


Atmosphere

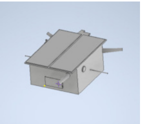
Earth Modeling

→ Binary image Comparison

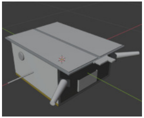


3D Model of the Spacecraft

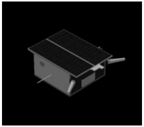
⟶ Based on the TANGO spacecraft from the PRISMA mission:



CAD



Blender



POV-Ray

- CAD is created using Autodesk Inventor
- Imported in Blender to exploit POV-Ray add-on
- Textures are applied
- Optical parameters are defined
- SDL code is hand-tuned to allow reusability

⟶ Process has to be carried out only one time

Simulate a real camera

→ POV-Ray allows to set camera aperture angle:

$$A.R. = \frac{N_u}{N_v}$$

$$CCD_{size} = d_u \cdot N_u$$

$$\alpha = 2 \cdot \arctan\left(\frac{CCD_{size}}{2 \cdot f_x}\right)$$

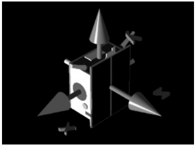
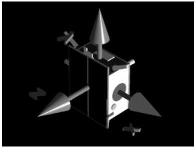
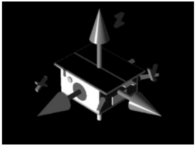
N_u	Number of horizontal pixels
N_v	Number of vertical pixels
f_x	Horizontal focal length
f_y	Vertical focal length
d_u	Horizontal pixel length
d_v	Vertical pixel length

→ Under the assumption of square CCD sensor having square pixels.

Reference Frames and Ground Truth Pose

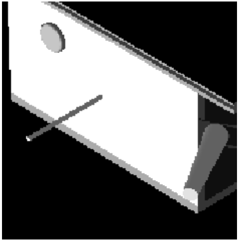
→ POV-Ray by default works using a Left Handed Coordinate System

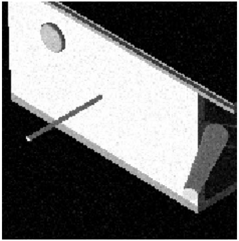
- Flip it to use a Right Handed Coordinate System
- Compute camera attitude by the knowledge of camera position and camera looking direction
- Compute ground truth pose by knowledge of camera attitude and target attitude

Add Gaussian withe noise and speckle noise

⟶ To enhance the fidelity noise is added to the image





Speckle: $\sigma^2 = 0.004$
Gaussian: $\sigma^2 = 0.003$

MATLAB Integration

Simulink Model

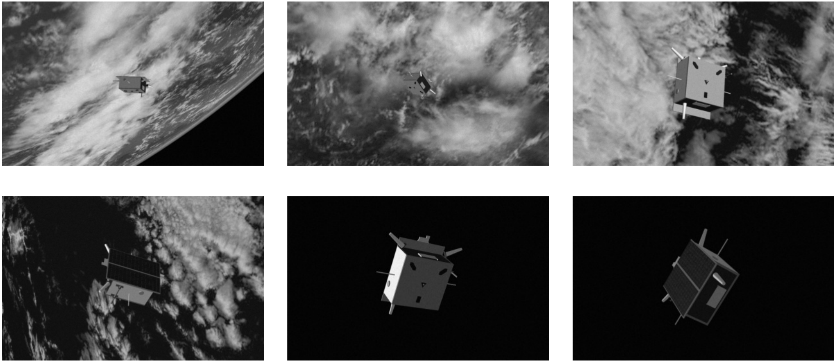
- Simulate uncontrolled behavior on LEO orbit
- Easily extendable to include controlled behavior too
- Chaser constrained to be between 3 to 18 meters far from the target
- Extendable to simulate precise chaser approach

MATLAB Functions

- Write `.pov` SDL files for each image
- Annotate ground truth pose for each image
- Sets relevant POV-Ray options and run it
- Can re-parse ground truth pose for each image

Results

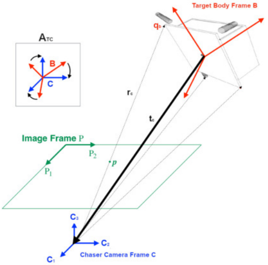
Samples



WARNING: Custom POV-Ray version needed to replicate results!

The SVD Architecture for Pose Initialization

Pose estimation problem



2D/3D true perspective equations

$$\mathrm{r_C} = \begin{bmatrix} x_C & y_C & z_C \end{bmatrix}^T = \mathrm{A_{TC}}\, \mathrm{q_B} + \mathrm{t_C}$$

$$\mathrm{p} = \left[\frac{x_C}{z_C} f_x + C_x, \ \frac{y_C}{z_C} f_y + C_y \right]$$

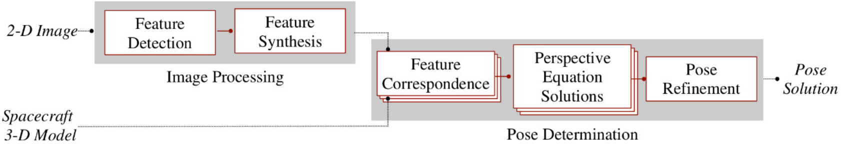
$$\longrightarrow (\mathrm{A_{TC}}, \mathrm{t_C}) \longleftarrow$$

- Highly non linear and can have ∞ solutions if undercostrained
- No *a priori* knowledge of the correspondence between $\mathrm{q_B}$ and p
- Image has to be corrected for pixel's non-quadratism and lens distortion

Feature-based pose estimation

General architecture

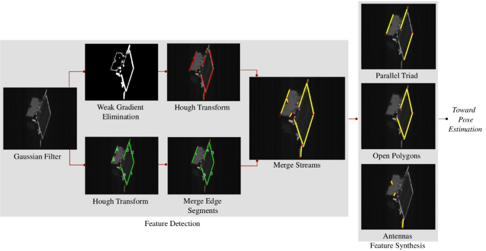
→ **Custom re-implementation of SVD algorithm from the ground up**



→ **Enhance current State-of-the-art**

- Introduces WGE technique which allows to distinguish S/C from background and allows to determine a ROI
- Uses 2D/3D feature groups to solve feature correspondence problem

Image processing subsystem - 1



→ Two streams of features are extracted using Hough transform:
- WGE stream
- S&H stream

→ Multiple truncated edges are merged into one line

→ Features are organized in perceptual groups

- The knowledge of the ROI allows to tune Hough hyperparameters adaptively to obtain desired behavior
- Edges outside the ROI are rejected

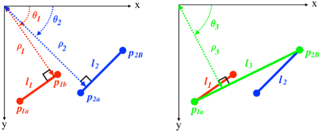
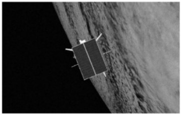


Image processing subsystem - 2

→ **Weak Gradient Eliminator**

Most of the gradient intensities are weak and corresponds to the feature in the background or on the spacecraft surface.



Original image

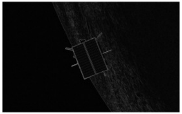
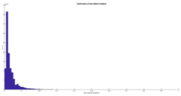
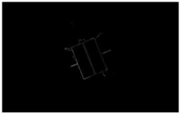


Image gradient



Histogram



Filtered image

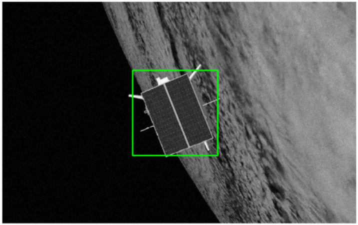
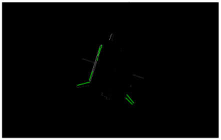


Image processing subsystem - 3

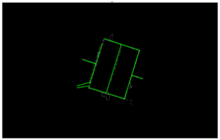
→ **Custom implementation**

- ROI it's enlarged by adding the 5% of the mean detected edge length to not penalize images presenting a black background
- Prior applying Hough transform to the Sobel image, to eliminate the pixel chunks belonging to smaller reflective elements from the output of Hough, all connected components (objects) that have fewer than P pixels from the input binary image are removed
- The edge merging procedure is applied to both streams

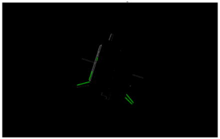
Image processing subsystem - 4



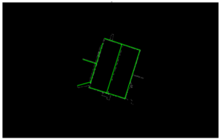
WGE stream



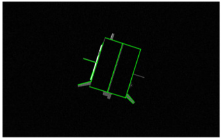
S&H stream



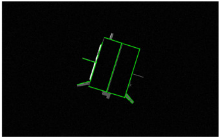
WGE merge



S&H merge



WGE + S&H

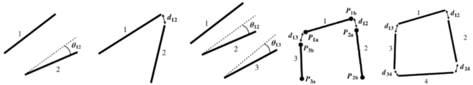


Merge stream

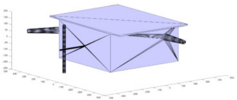
Perceptual Grouping

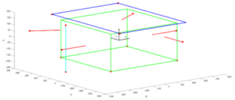
→ **Allows to reduce the search space of the correspondence problem**

Perceptual groups are defined on the basis of some geometrical constraints



Parallel Pair | Proximity Pair | Parallel Triad | Proximity Triad | Closed Polygonal Tetrad

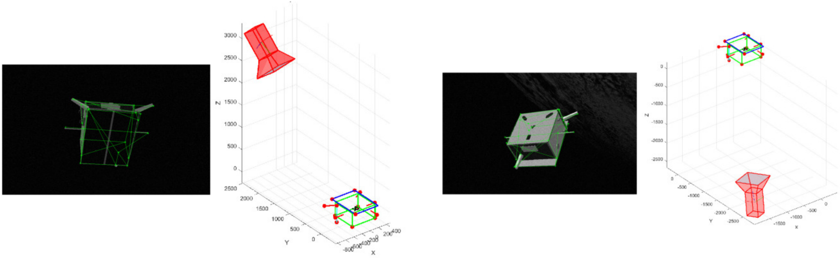




- Carried out on a wireframe model too by applying 3D geometry definitions instead of 2D ones

Successful pose initialization

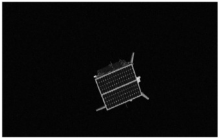
→ Obtained using P3P solver coupled with a RANSAC algorithm for outlier rejection instead of ePnP



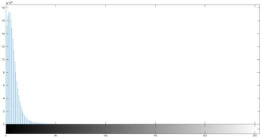
Figures are showing the map superposed to the image and the 3D camera pose in map coordinates

Results

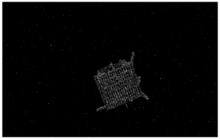
SPEED VS Implemented Tool



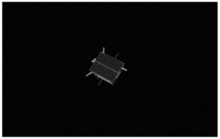
Unfiltered Image



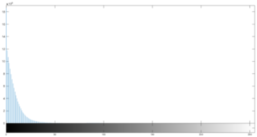
Histogram



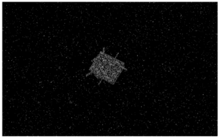
Sobel Image



Unfiltered Image

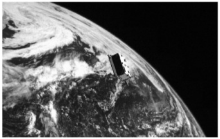


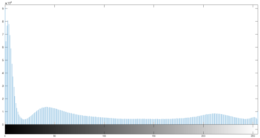
Histogram

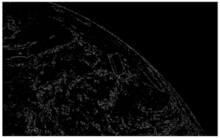


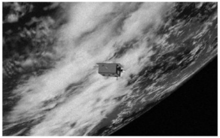
Sobel Image

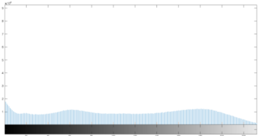
SPEED VS Implemented Tool

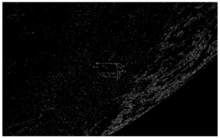

Unfiltered Image


Histogram


Sobel Image

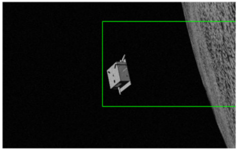

Unfiltered Image


Histogram

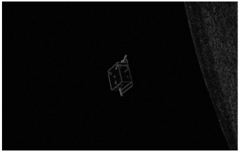

Sobel Image

Failures

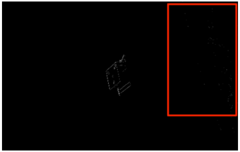
ROI Detection ⟶ Due to composite background



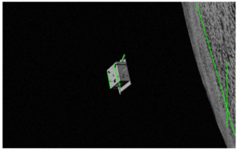
Detected ROI



Normalized Gradient



Tresholded Gradient

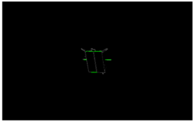


Edge Detection

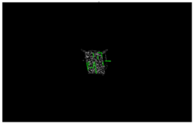
SVD Algorithm

Failures

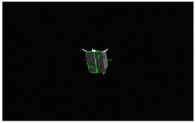
Edge Detection ⟶ Due to solar panels or distance



WGE Stream

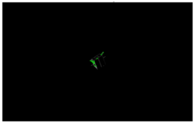


S&H Stream

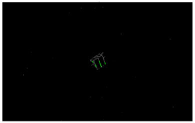


Merging streams

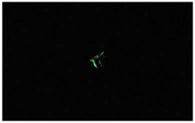
Tresholded Gradient



WGE Stream



S&H Stream

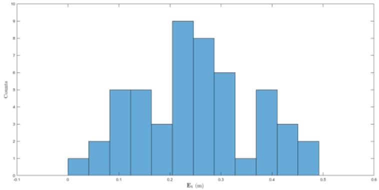


Merging Streams

Rotational and translational errors

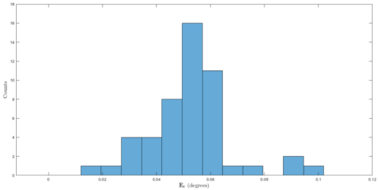
Translational Error

→ Mean error: 0.2506 m



Rotational Error

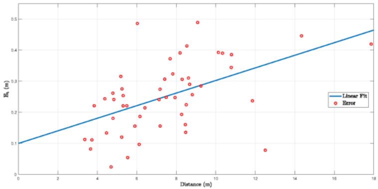
→ Mean error: 0.0528°



Errors WRT inter-spacecraft distance

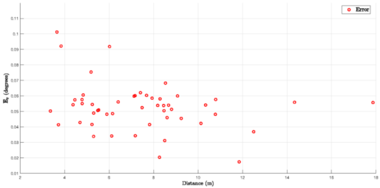
Translational Error

→ Increases with distance



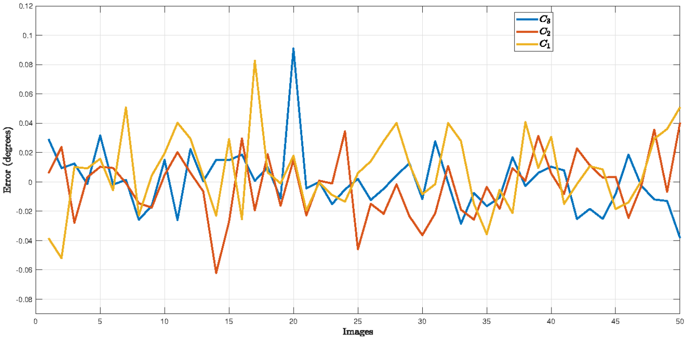
Rotational Error

→ No recognizable trend



Camera axis error

→ No preferred axis



Conclusions

Image Generation Tool

- → Image toolbox is fully automated
- → Controlled and uncontrolled behavior can be simulated as well as well as approach
- → Generated images seems are promising

SVD Algorithm

- → Successfully tested SVD algorithm
- → Results seems to be promising

Improvements

Image Generation Tool

- → Use better textures for the S/C and the Earth
- → Use a more rigorous method to set optical parameters
- → Improve noise model
- → Patch POV-Ray code to allow GPU cores usage for rendering

SVD Algorithm

- → Employ separated Hough transforms to detect different geometric shapes
- → Improve edge detection procedure (solar panels, distance are an issue)
- → Compare different pose solvers
- → Hardware-in-the-loop experiments to evaluate the computational time on real H/W.

The End

Thanks for your attention