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Pose Estimation of Uncooperative Spacecraft using Monocular Vision

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Problem Statement

Utilizing a 3D model of an uncooperative target spacecraft in conjunction with monocular vision from a servicer spacecraft to estimate pose of the target relative to the servicer

prismasatellites.se

Overview

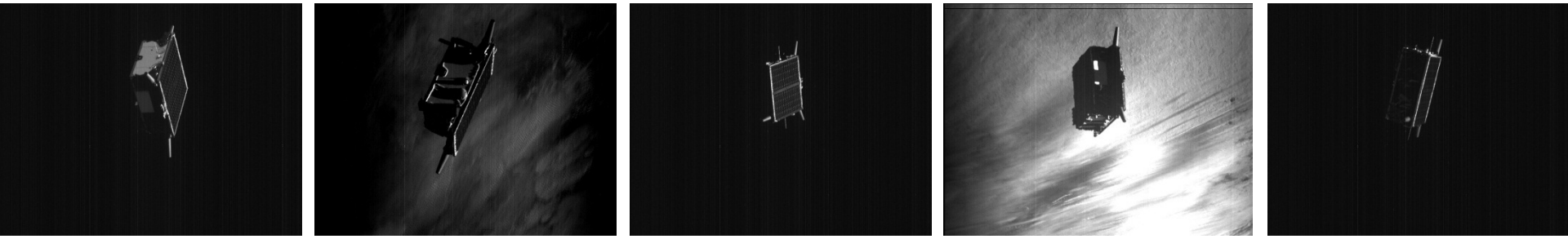
- Motivation
- Survey of state-of-the-art pose estimation
- Initial Pose Estimation
- Model Processing
- Image Rendering
- Comparative Assessment

ORBITAL EXPRESS VISCAM2

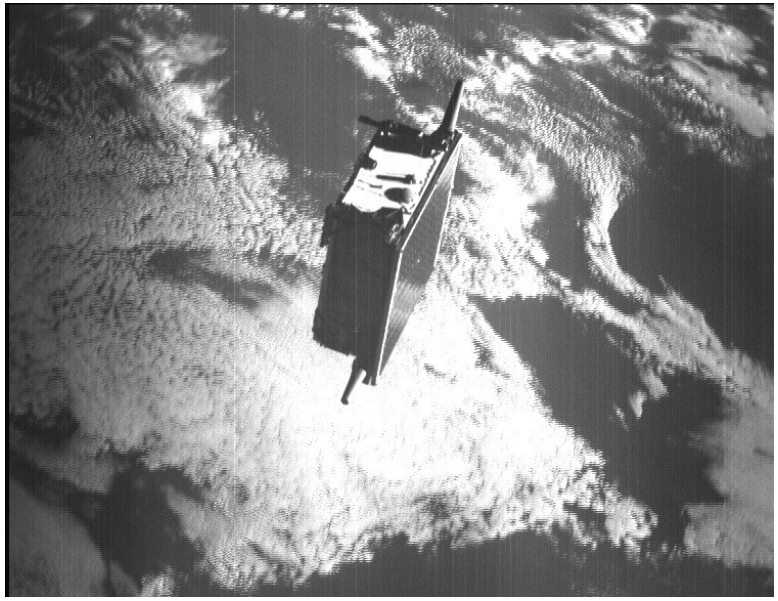
COURTESY: HTTP://ARCHIVE.DARPA.MIL/ORBITALEXPRESS/MISSION_UPDATES.HTML


PRISMA Mango
Avstånd: 7,6982 m
Radie: 1,3464 m
Apparent diameter: 17° 07' 20,8"
Phase angle: 94,0°
2010 Sep 14 19:55:20 UTC
20× snabbare
PRISMA PR Camera
Courtesy: OHB Sweden
Hastighet: 0,00000 m/s
Synfält: 26° 42' 59,3" (1,00×

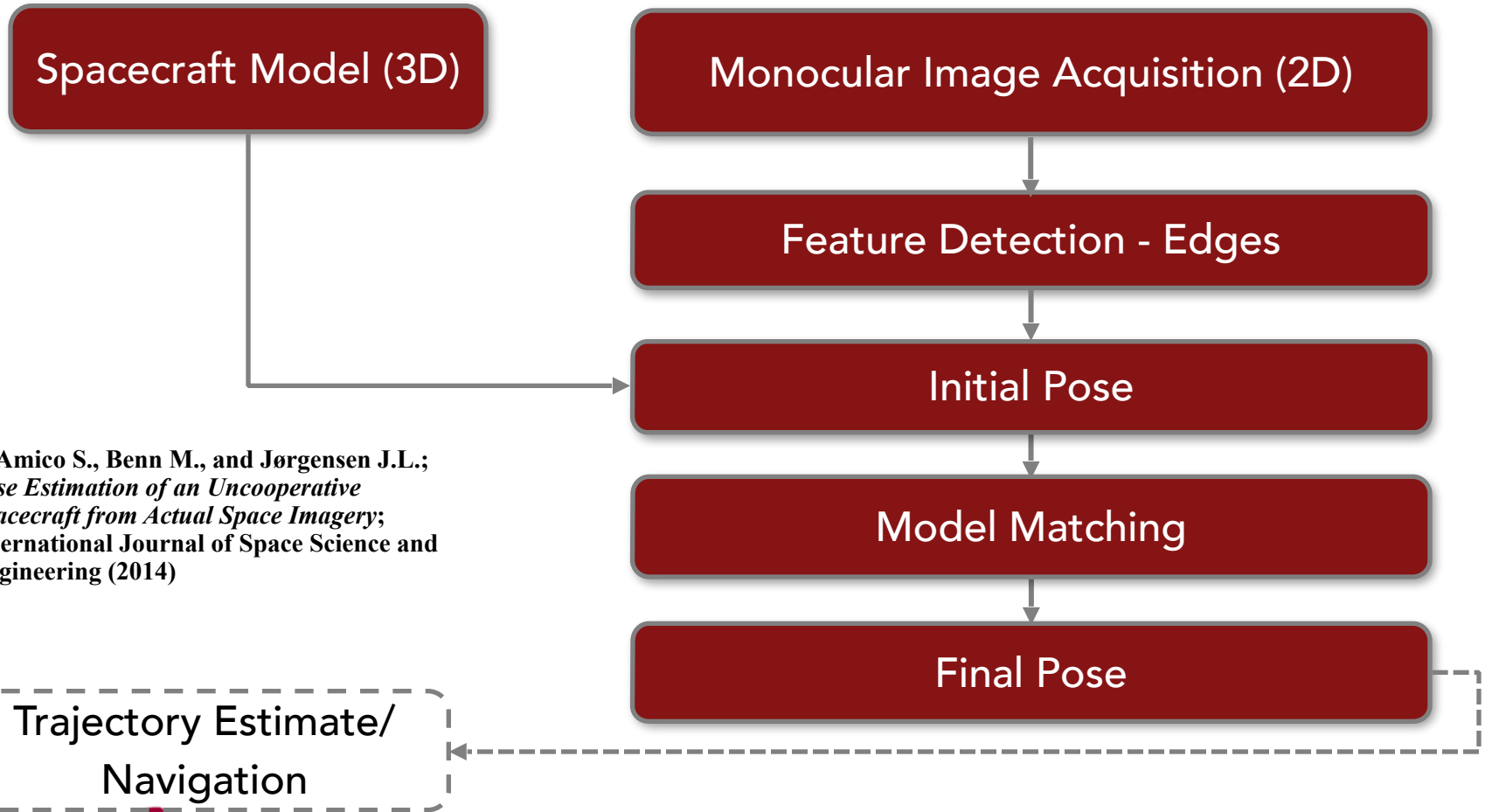
Challenges



- Carrier-to-Noise Ratio
- Scene illumination
- Processing limitations
- Low image acquisition rate
- Background interaction
- Occlusion
- Lack of depth information

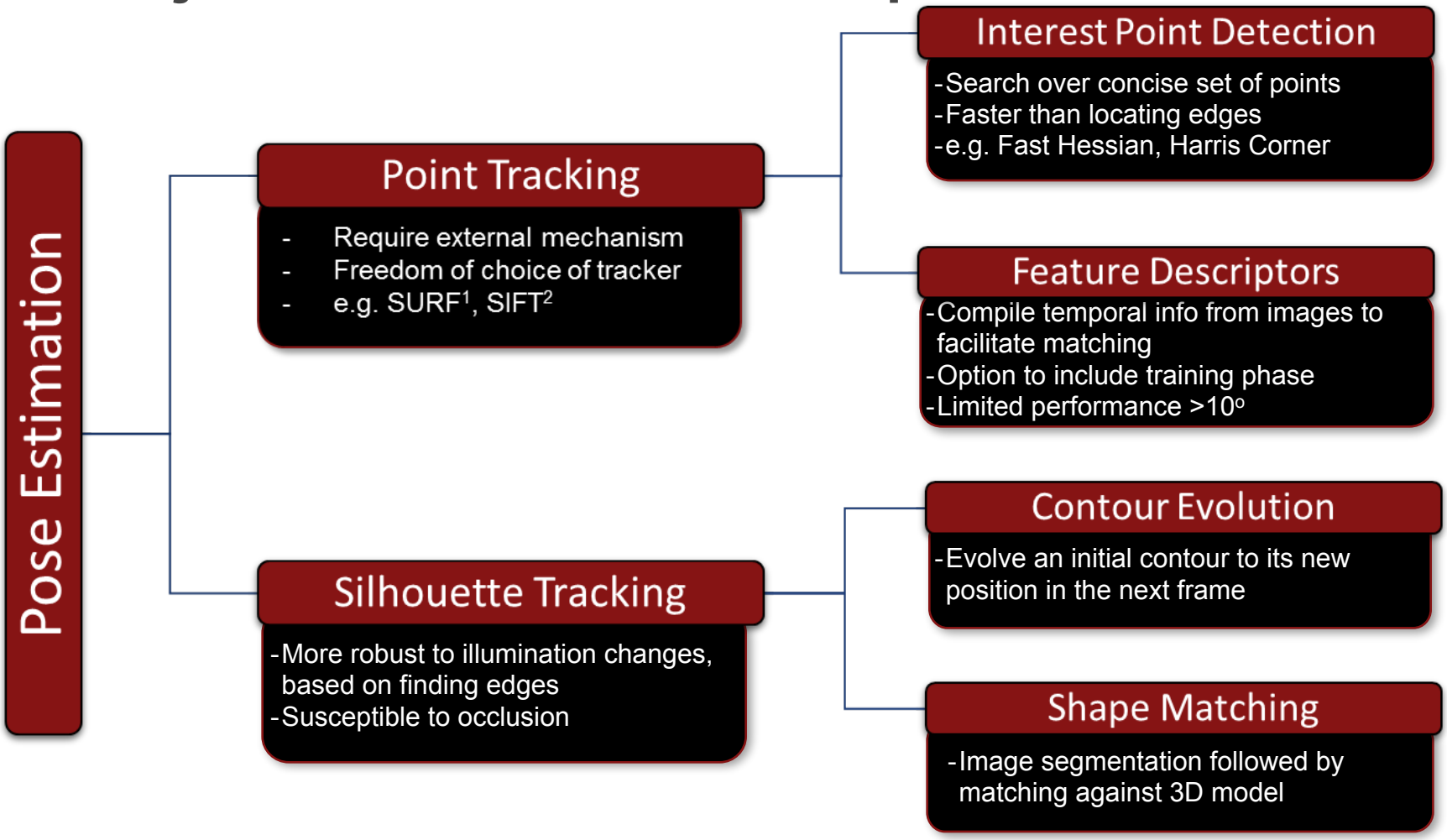


Previous Work



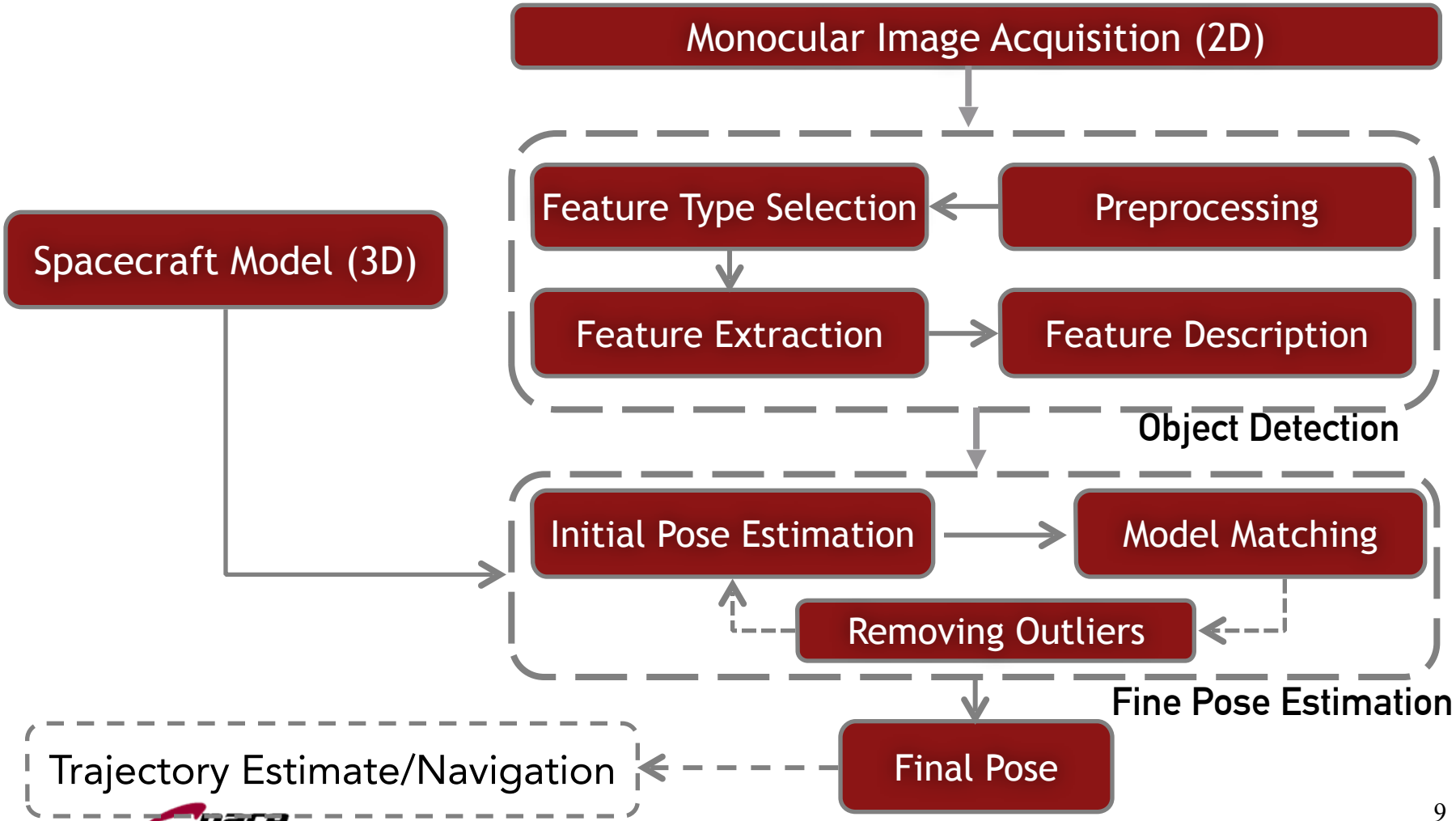
D'Amico S., Benn M., and Jørgensen J.L.; ***Pose Estimation of an Uncooperative Spacecraft from Actual Space Imagery*****; International Journal of Space Science and Engineering (2014)**

Survey of Pose Estimation Techniques

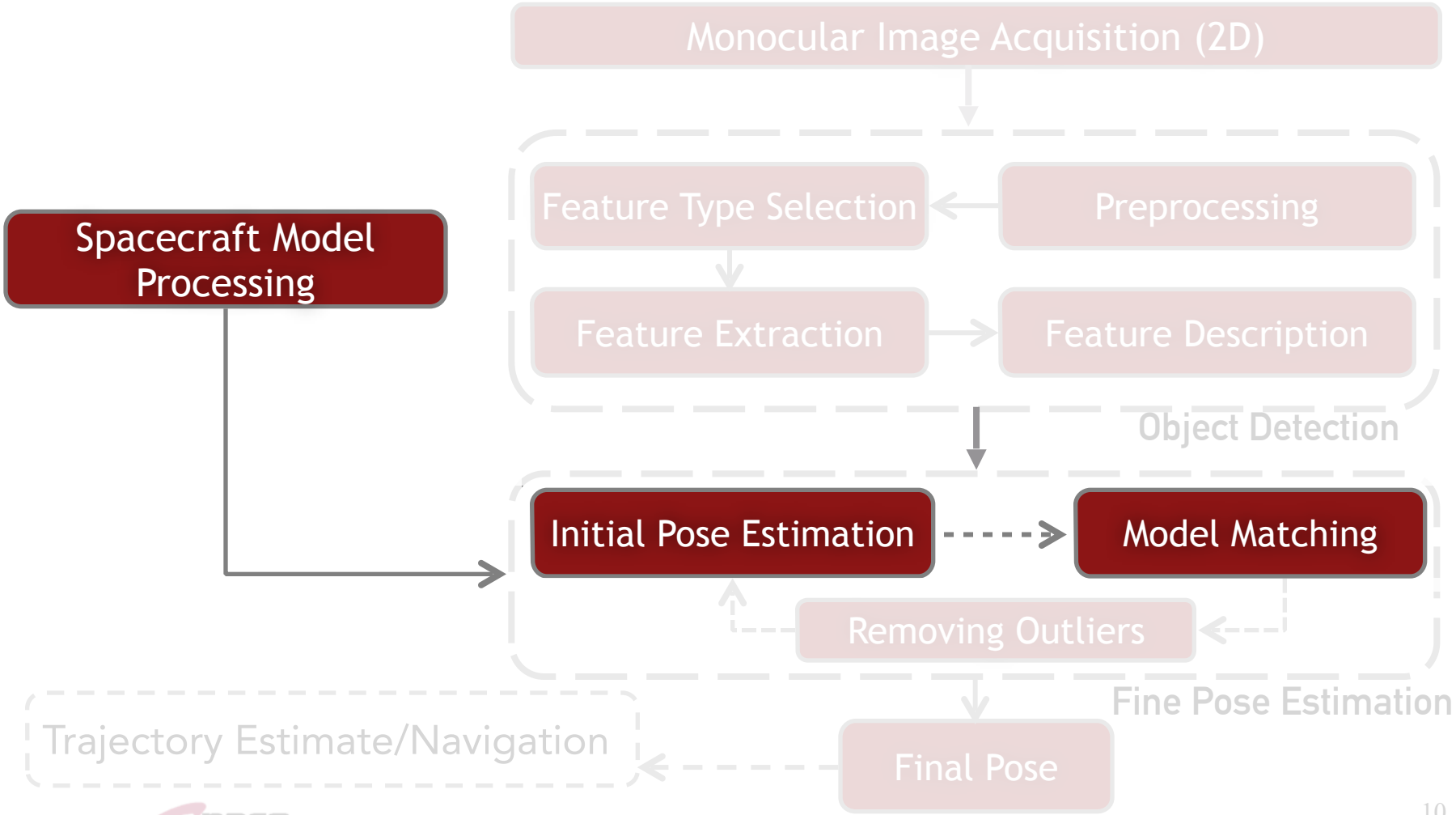


[1] [Bay 2006] [2] [Lowe 1999]

General Architecture



Focus of Present Work

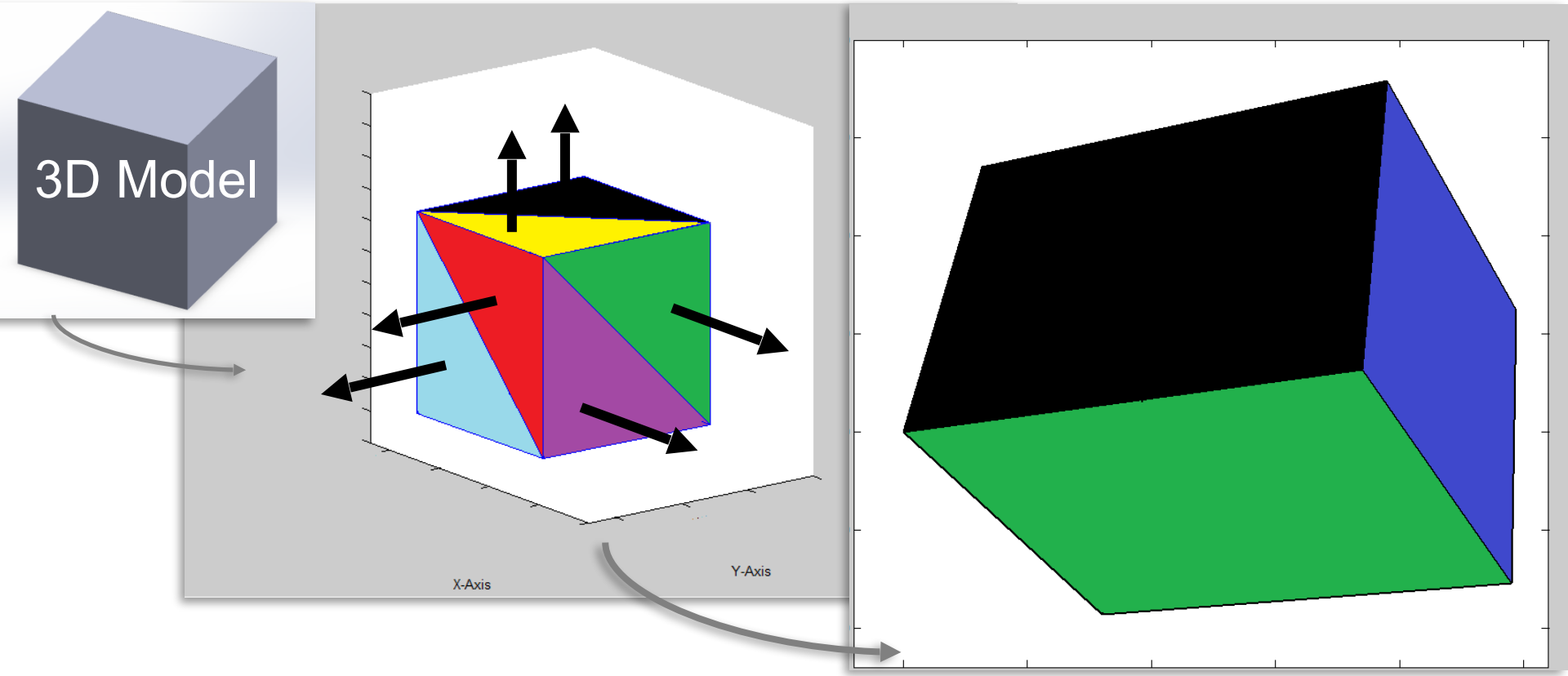


What do initial pose estimators do?

- Solve the perspective-n-point (PnP) problem
- Require "n" 3D model points and their 2D projections
- Require fully calibrated perspective camera

Model Processing

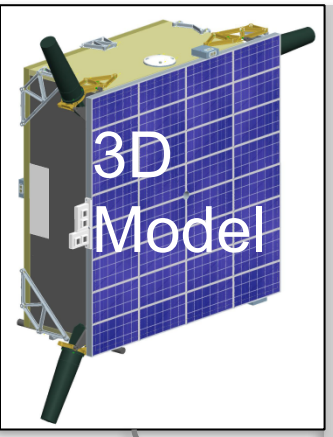
Meshing —.stl file→ Forming Edges —[points, edge list]→ Camera perspective control

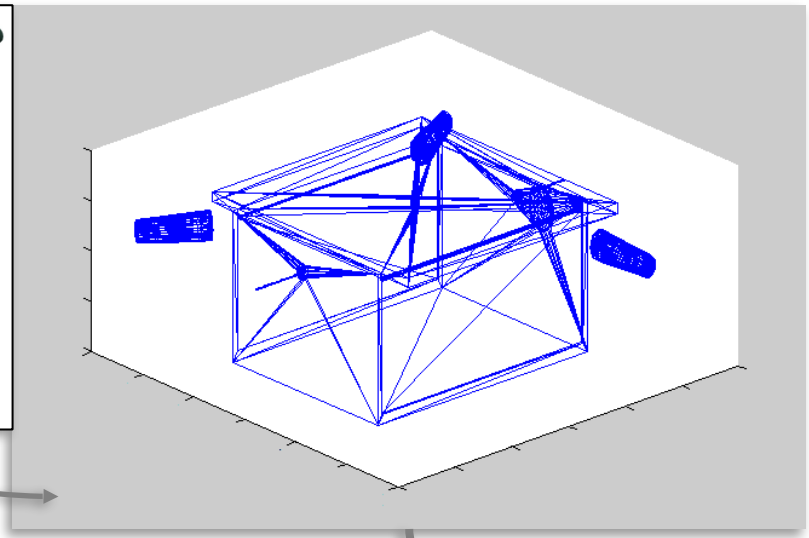


Model Processing & Reduction

Meshing —.stl file→ Forming Edges —[points, edge list]→ Camera perspective control

tolerance for curves





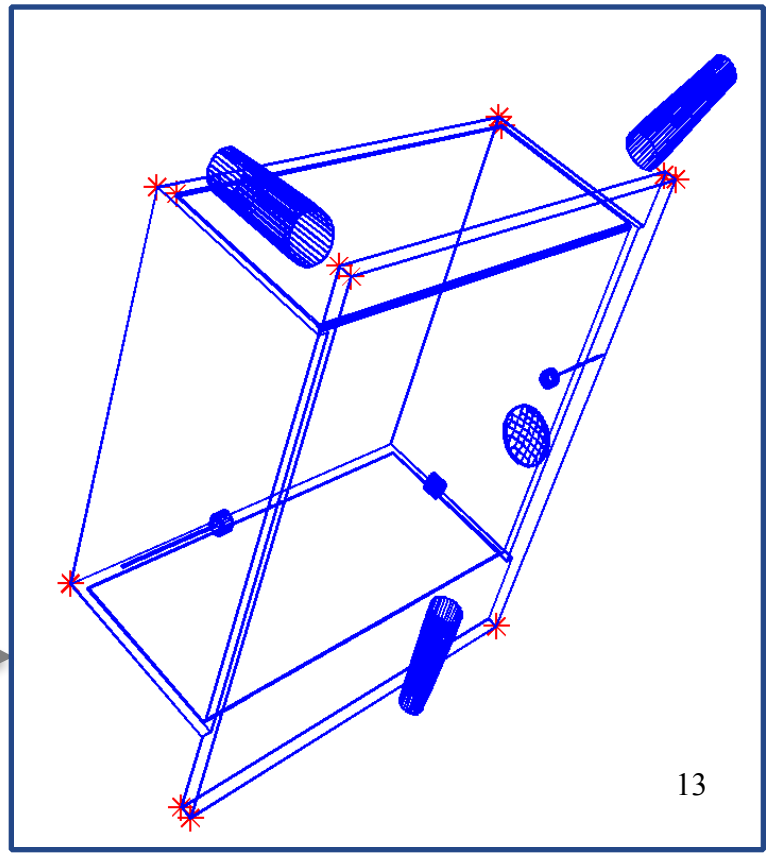
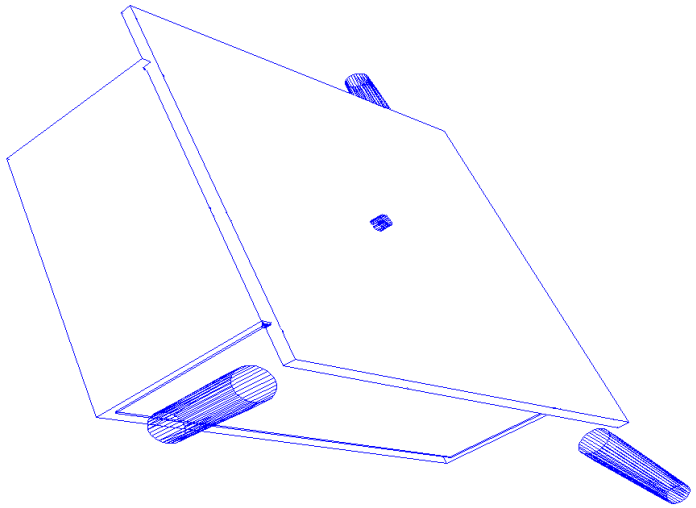
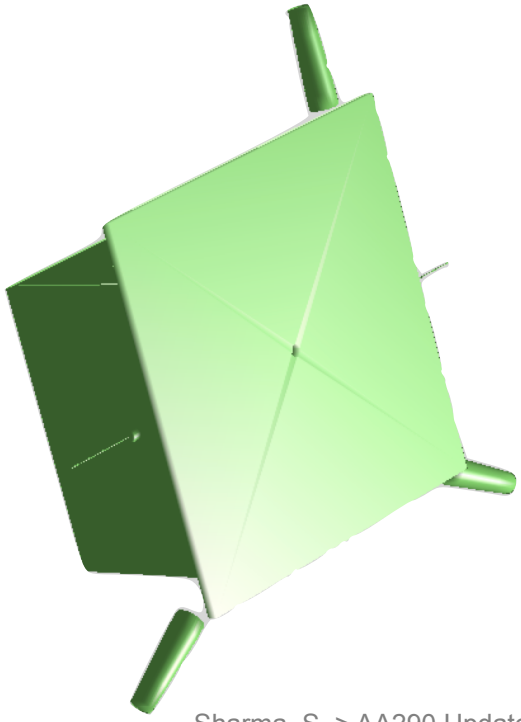


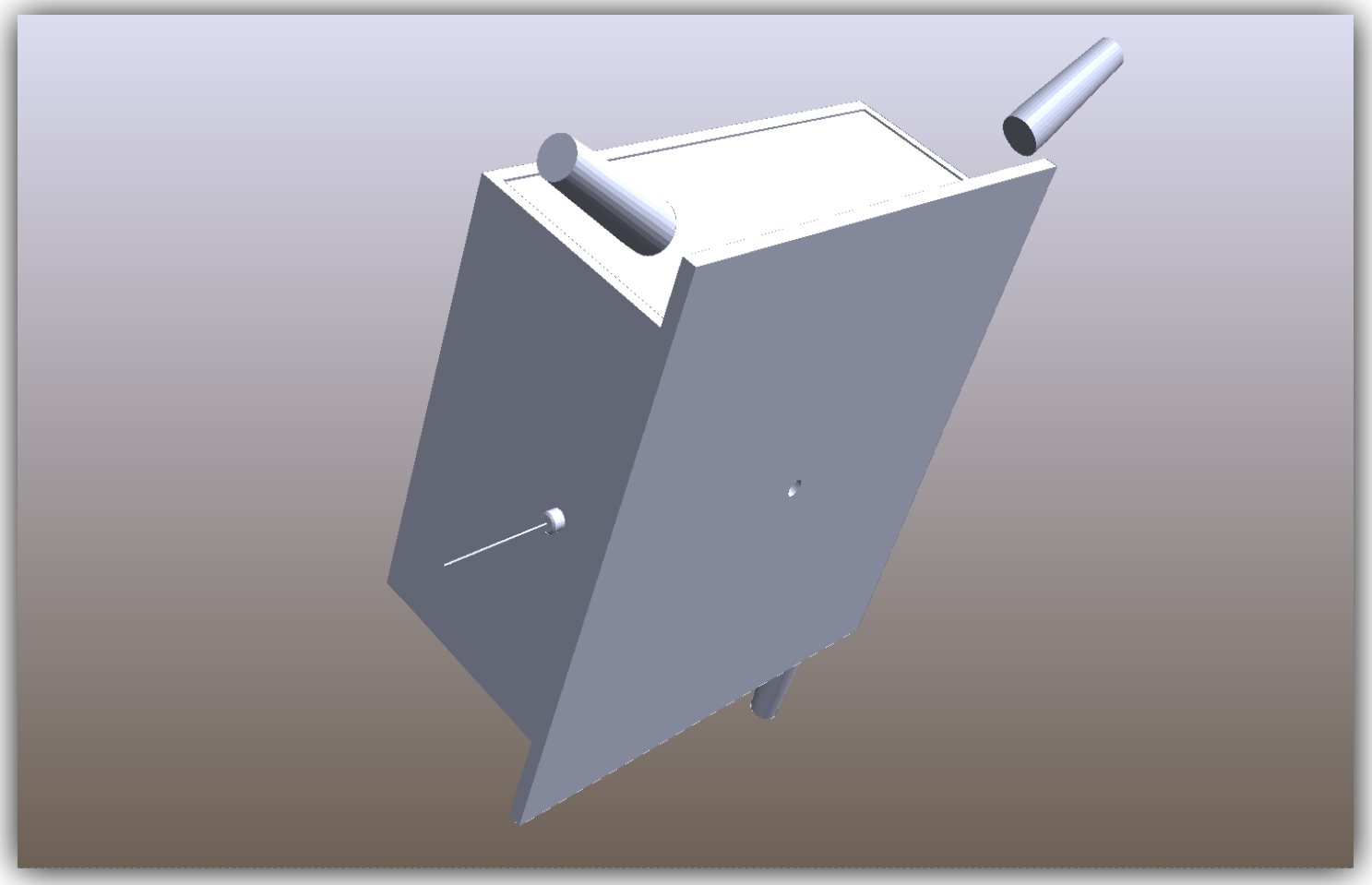
Image Rendering

- Complimentary (not a replacement) to images captured by servicer
- Test bed of synthetic images to validate/train pose estimation techniques
- Light control and Camera perspective control

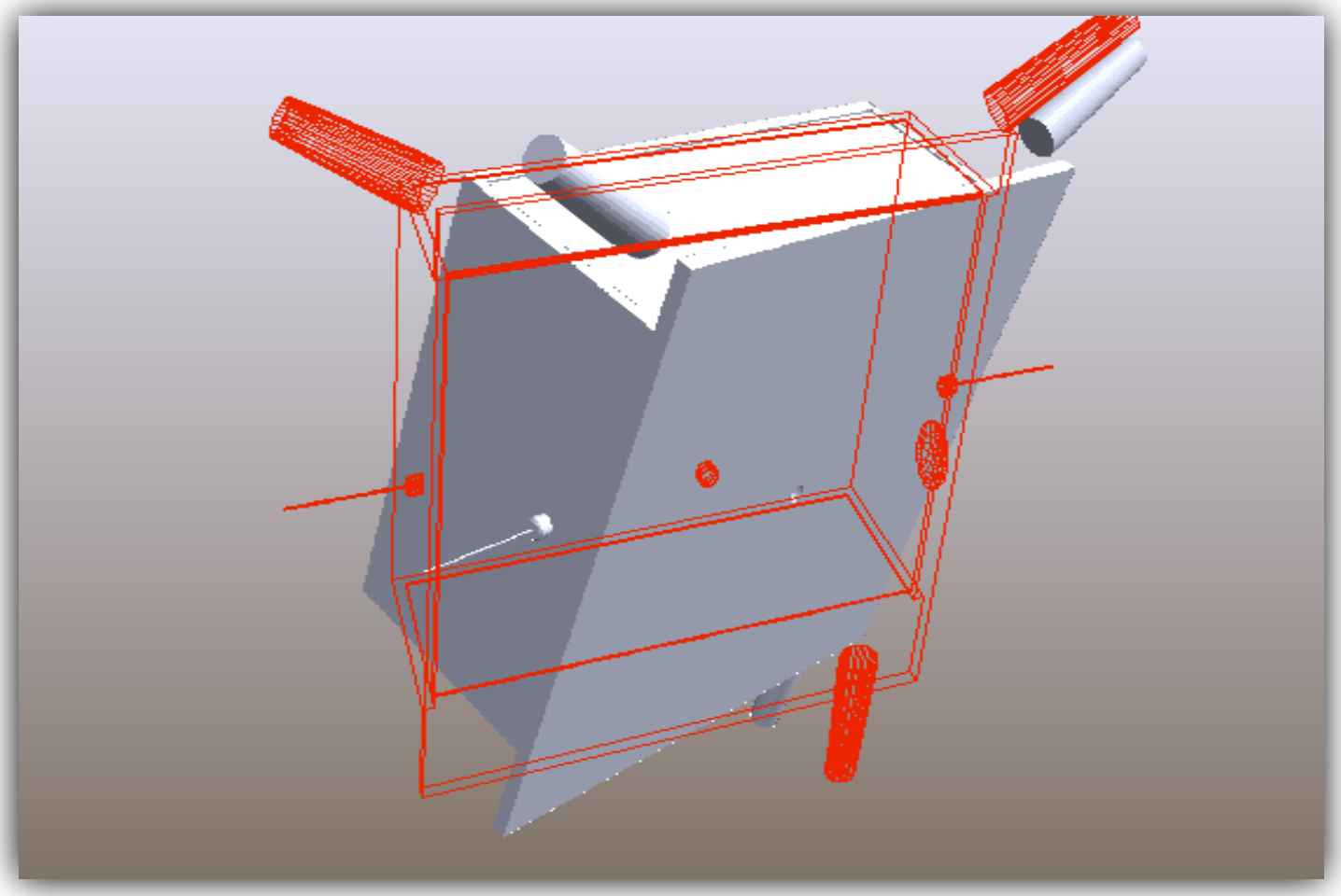




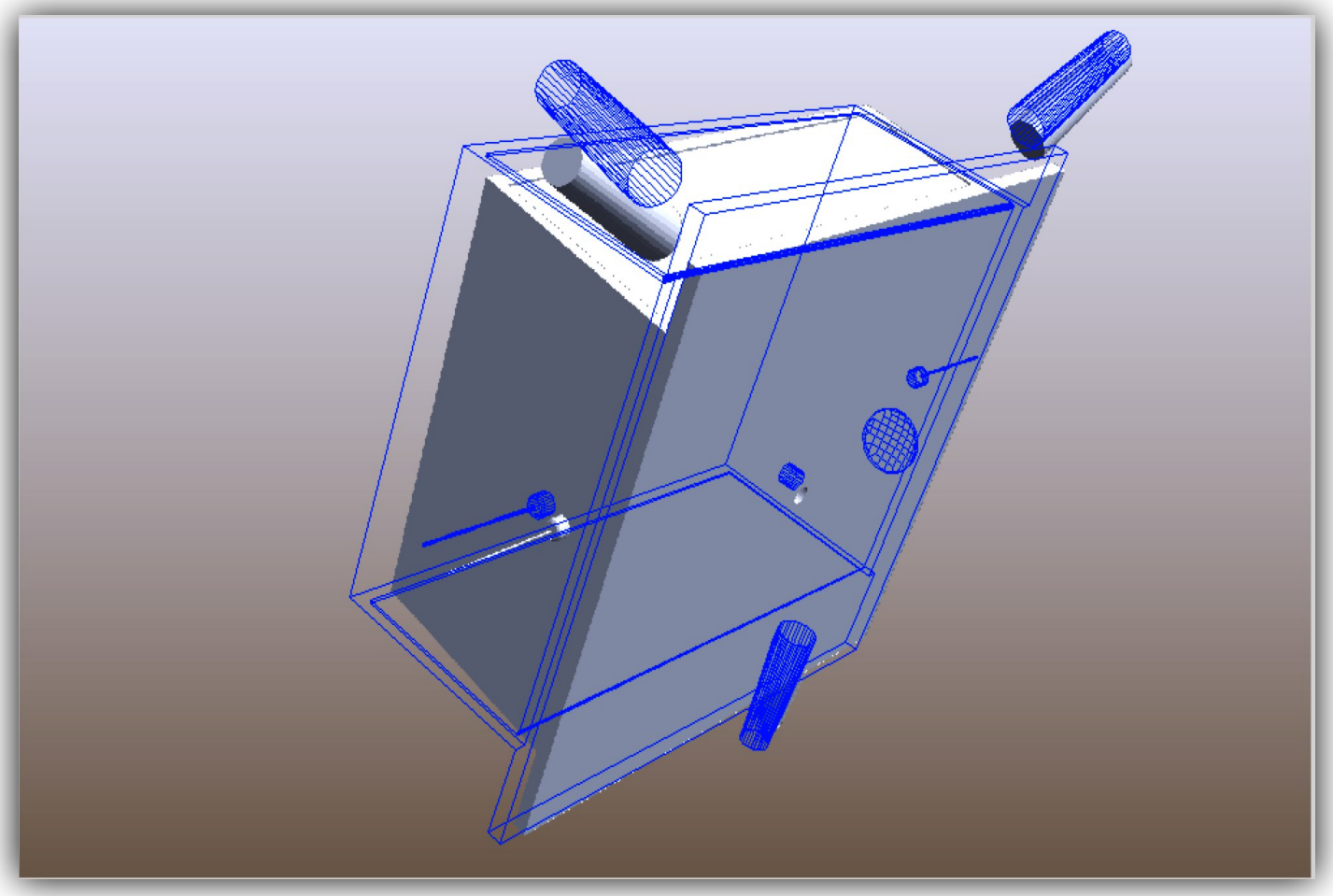
Initial Pose Estimate



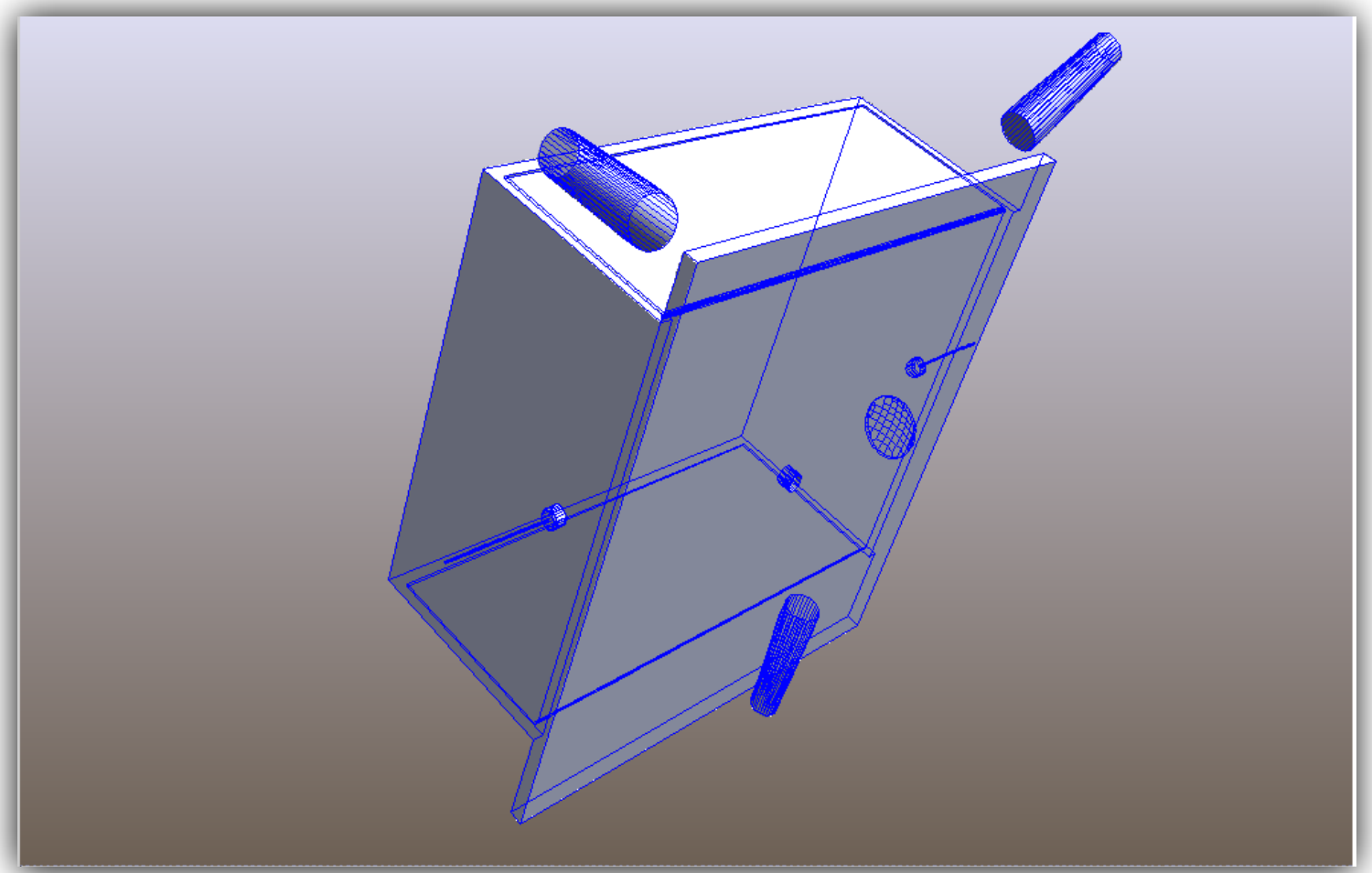
Initial Pose Estimate



Initial Pose Estimate

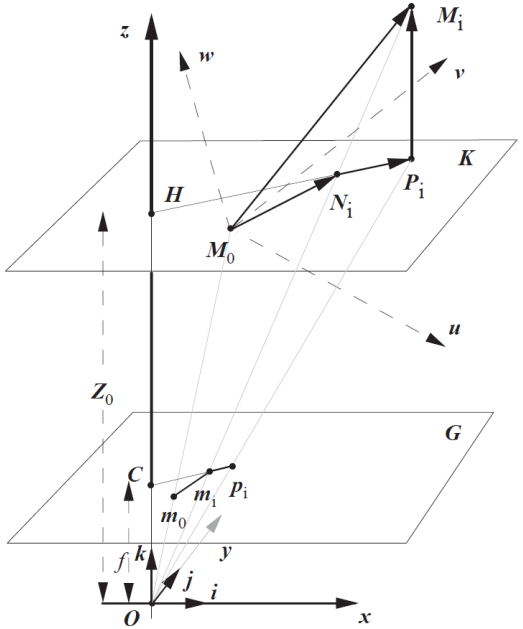


Final Pose Estimate



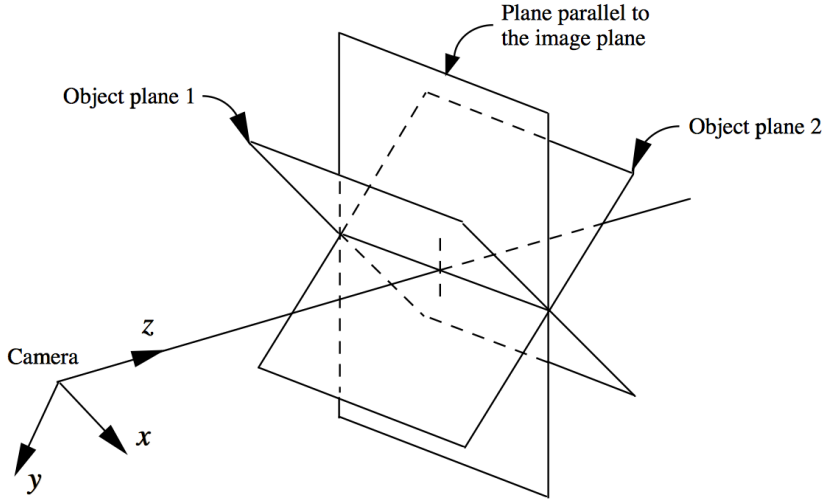
Initial Pose Estimate - POSIT

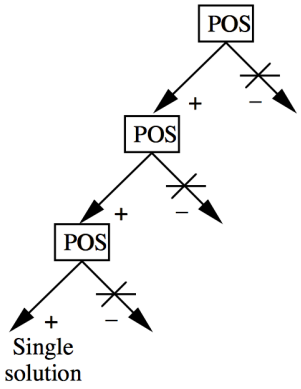
- Developed by Dementhon and Davis solves PnP problem
- Does not require initial pose estimate, iteratively solves to satisfy tolerance
- Does not handles coplanar points
- Input of minimum 4 correspondences

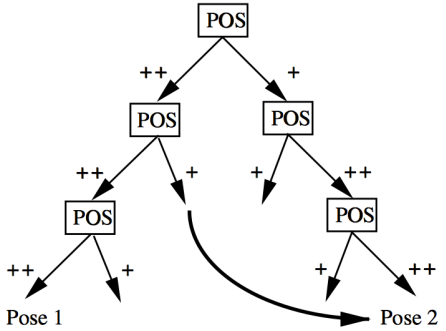


POSIT for Coplanar points

- Developed by Dementhon and Davis solves PnP problem
- Does not require initial pose estimate, iteratively solves to satisfy tolerance
- Handles coplanar points
- Input of minimum 4 correspondences

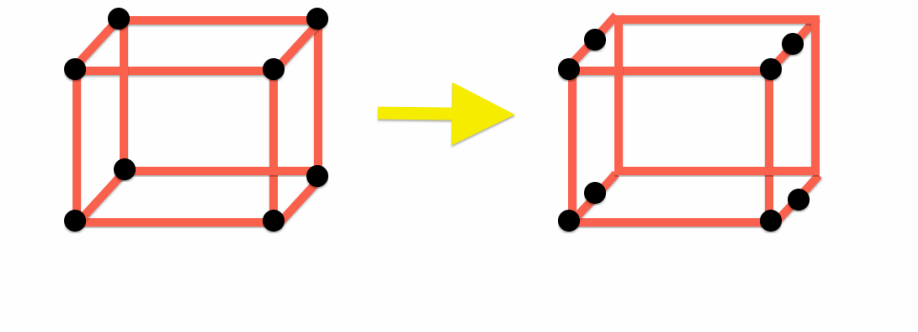






Coplanarity

- Tolerance of POSIT and Coplanar POSIT
- Coplanar POSIT worked <1.5e-14mm
- POSIT worked >2.5e-14mm
- Use of POSIT+



Initial Pose Estimate - EPnP

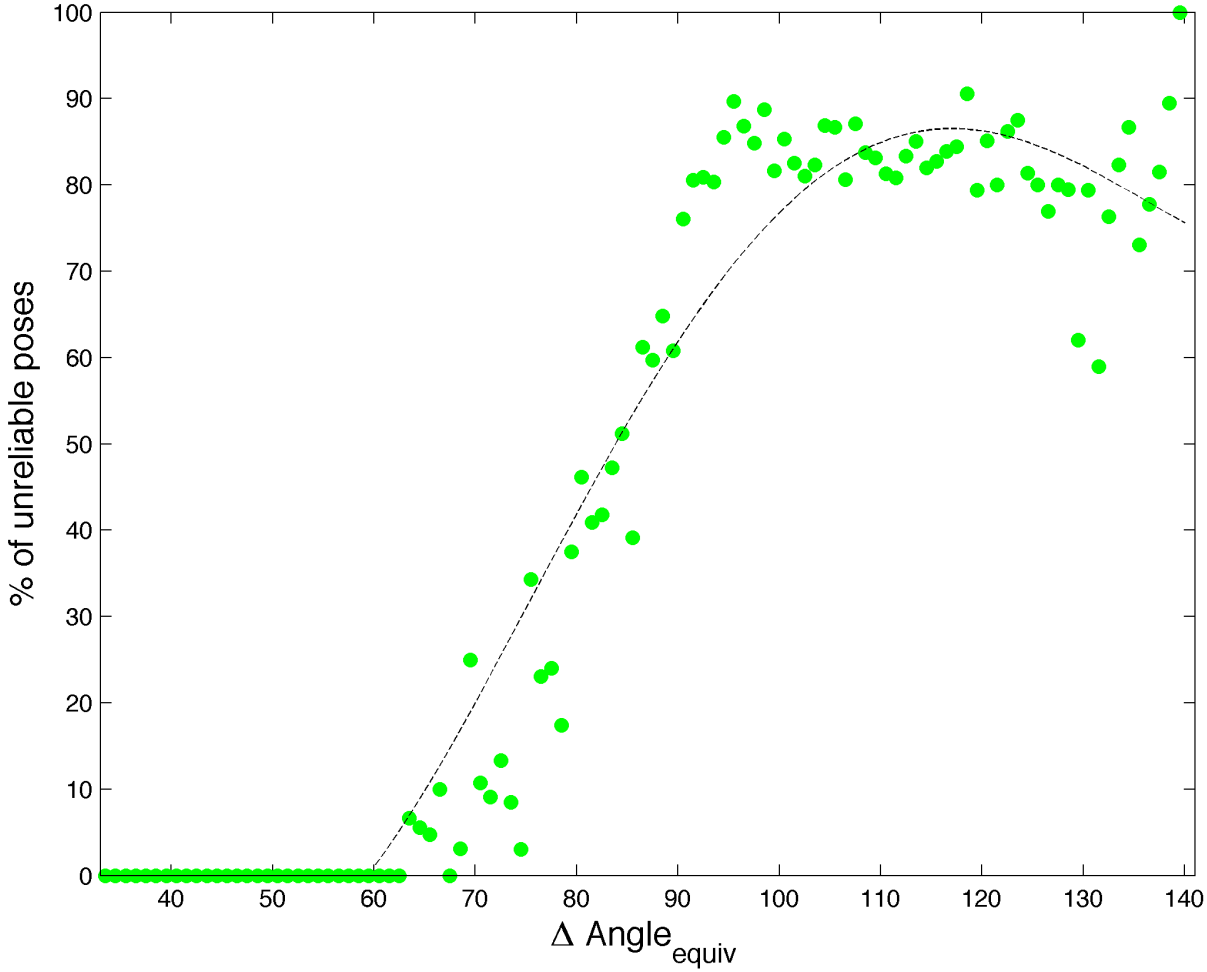
- Lepetit et al. (École polytechnique fédérale de Lausanne)
- Non-iterative O(n) solution to PnP problem
- Expresses n 3D points as a weighted sum of four virtual control points
- Use of Gauss Newton Optimization to select weights on control points
- Input of minimum 4 correspondences

Initial Pose Estimate - Newton Raphson

- Iterative solution to non-linear perspective equations
- Requires a-priori information about pose
- Inverts a 6x6 Jacobian at each iteration

$$\boldsymbol{E} = \frac{\partial \boldsymbol{\rho}_{\mathrm{D}}}{\partial \boldsymbol{r}_{\mathrm{C}}} \frac{\partial \boldsymbol{r}_{\mathrm{C}}}{\partial \boldsymbol{t}_{\mathrm{B}}} \Delta \boldsymbol{t}_{\mathrm{B}} + \frac{\partial \boldsymbol{\rho}_{\mathrm{D}}}{\partial \boldsymbol{r}_{\mathrm{C}}} \frac{\partial \boldsymbol{r}_{\mathrm{C}}}{\partial \boldsymbol{\varphi}_{\mathrm{B}}} \Delta \boldsymbol{\varphi}_{\mathrm{BC}}$$

Newton-Raphson Reliability



Comparison of Initial Pose Estimators: Test Cases

# of Matched Pairs	Std Dev of Gaussian Noise	Coplanarity
# of Outliers, Distance of Outlier	Distance to Camera	Distribution (Perceptual/ Geometric)

Comparison of Initial Pose Estimators: Performance

Time (s)

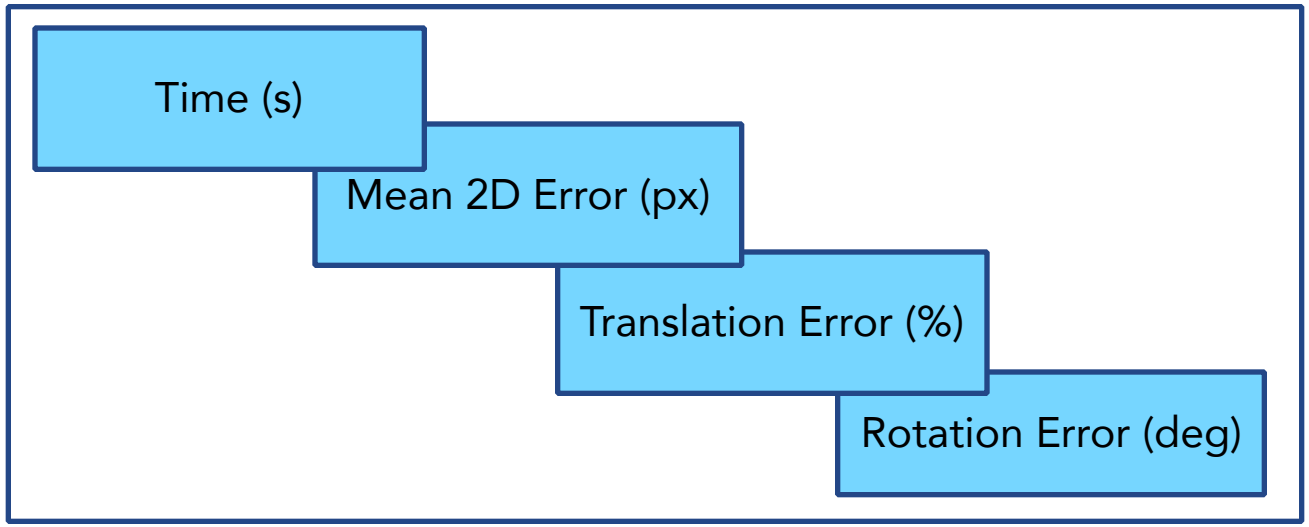
Mean 2D Error (px)

Rotation Error (deg)

Translation Error (%)

Decision Matrix

	Number of Points	Noise	Outliers	Distance to Camera
Posit				
Epnp				
Posit+				
Newton Raphson				



Comparison of Pose Estimators : Monte Carlo

- MATLAB Environment
- Computation time checked with multiple simulations
- Image generated with camera model used in PRISMA
- Reliability Check

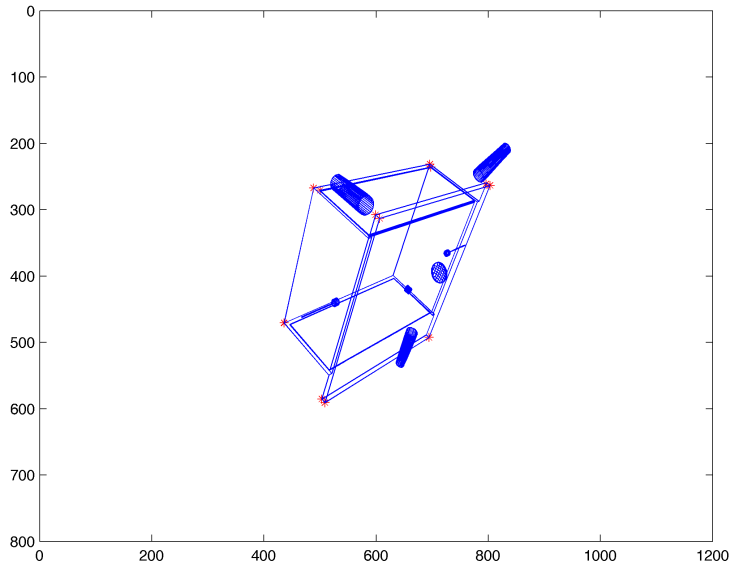
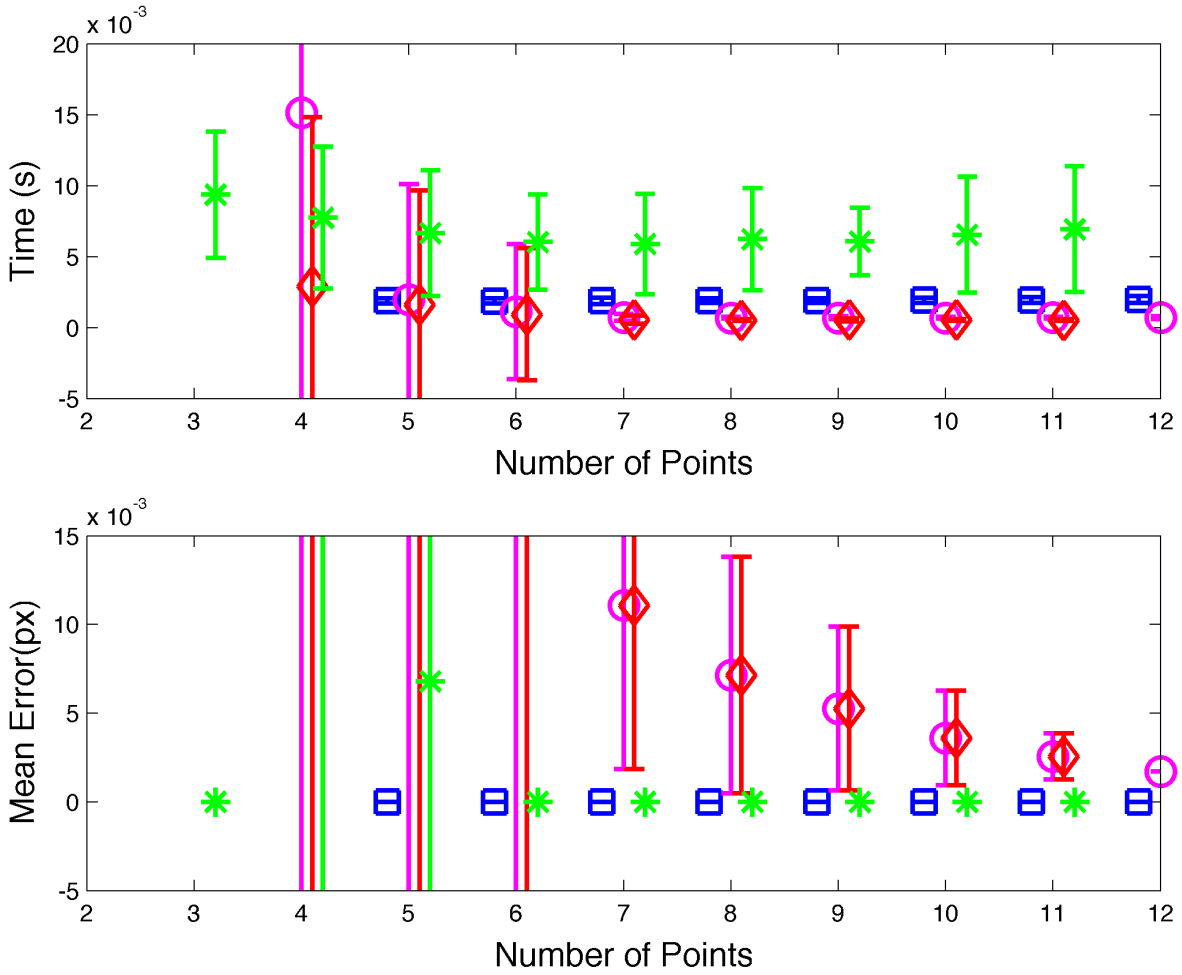
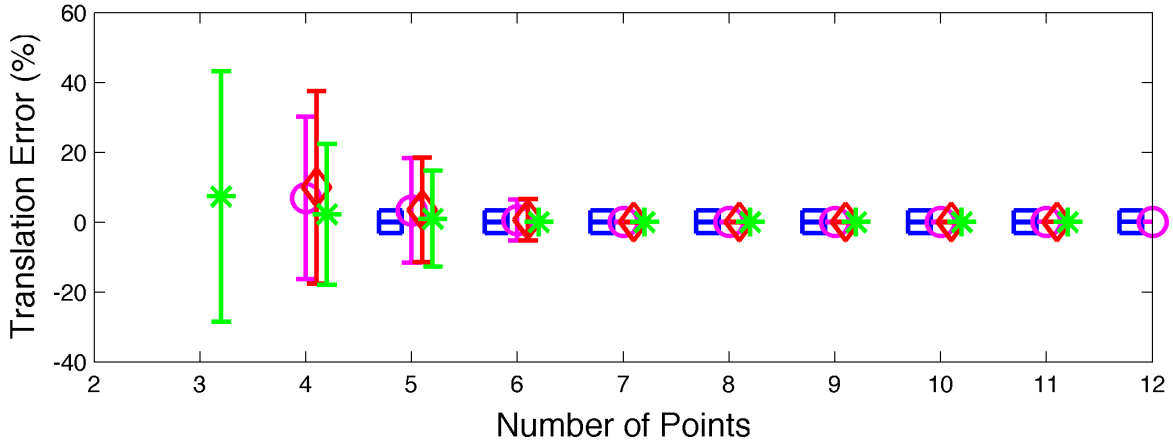


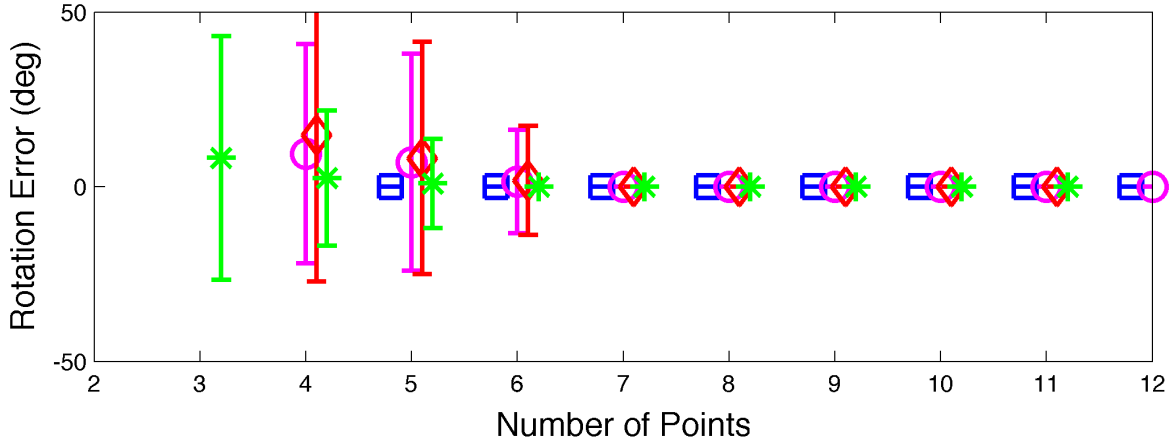
Image (ground truth) used for comparison

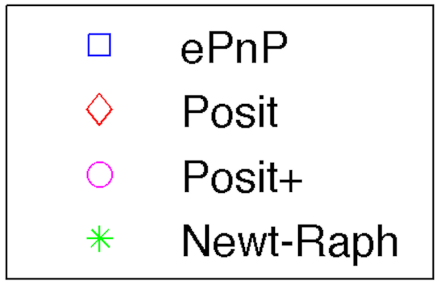
Criteria: Number of Matched Pairs



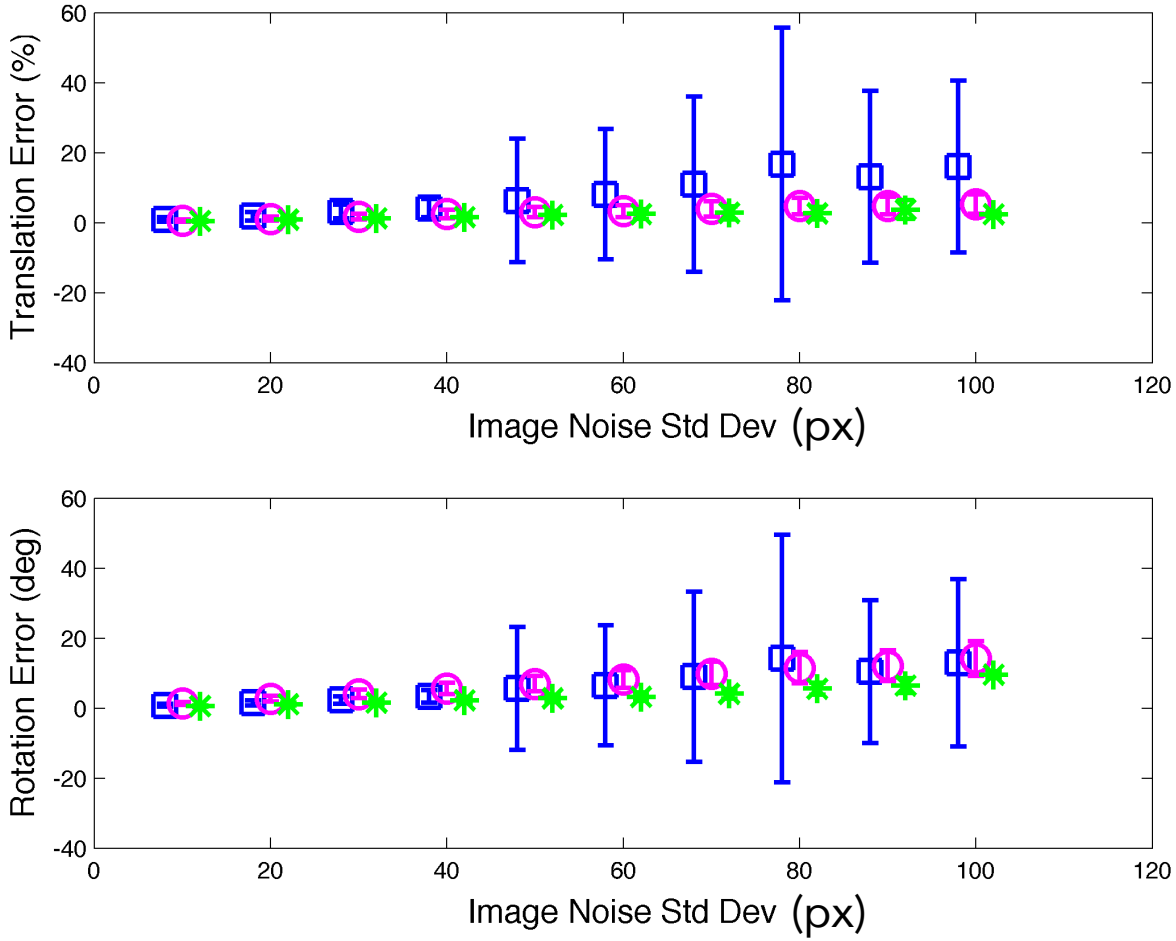
Criteria: Number of Matched Pairs

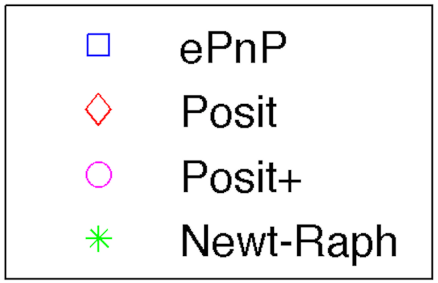




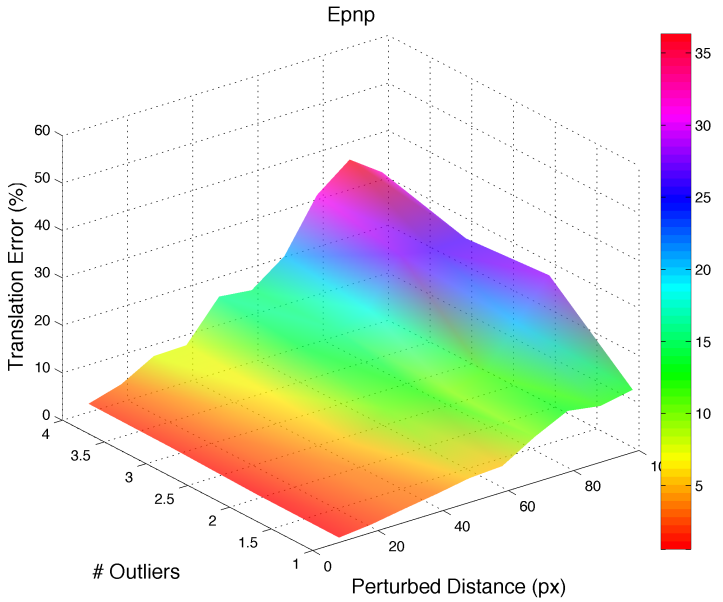


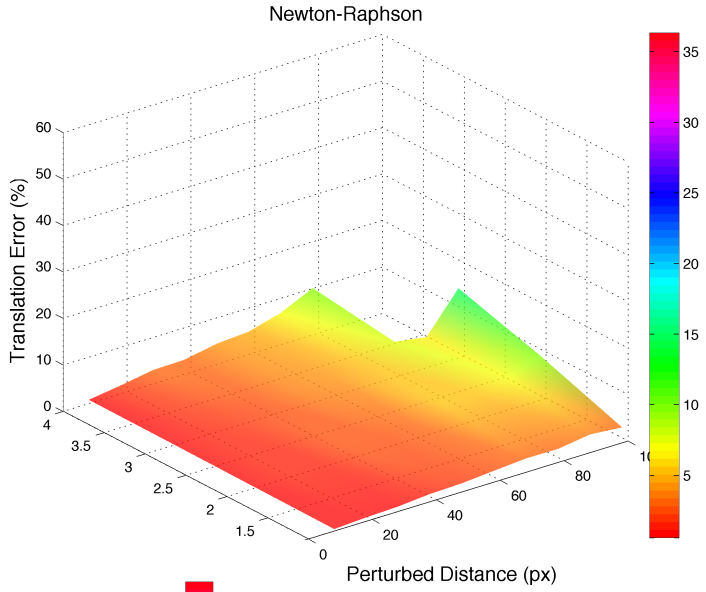
Gaussian Noise

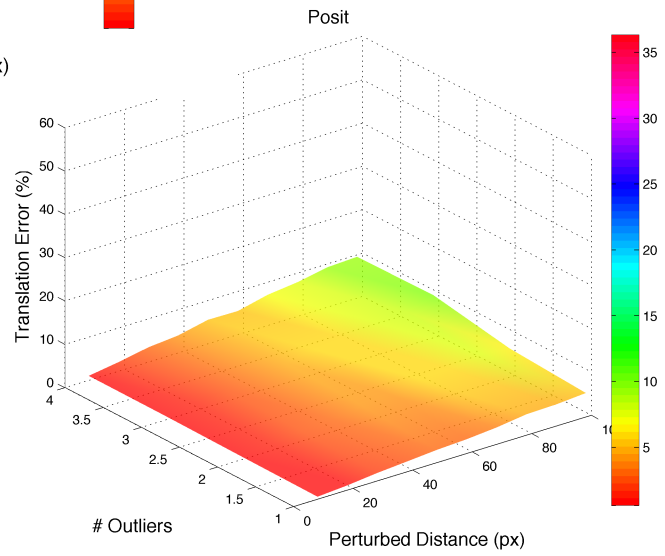




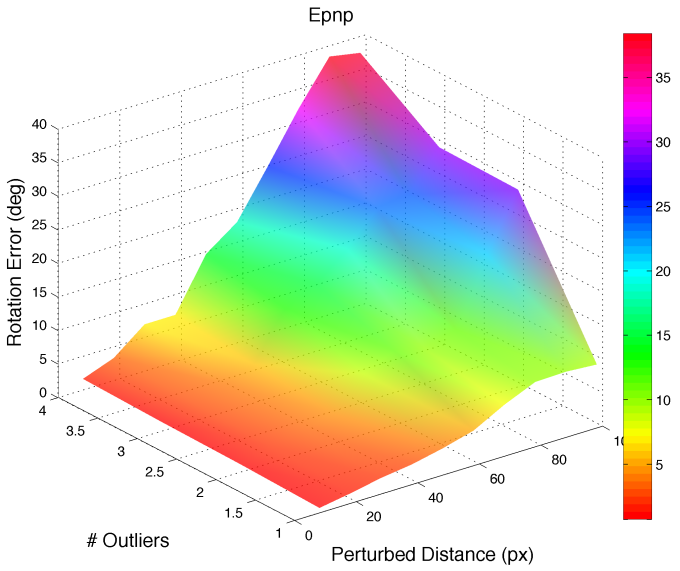
Outliers

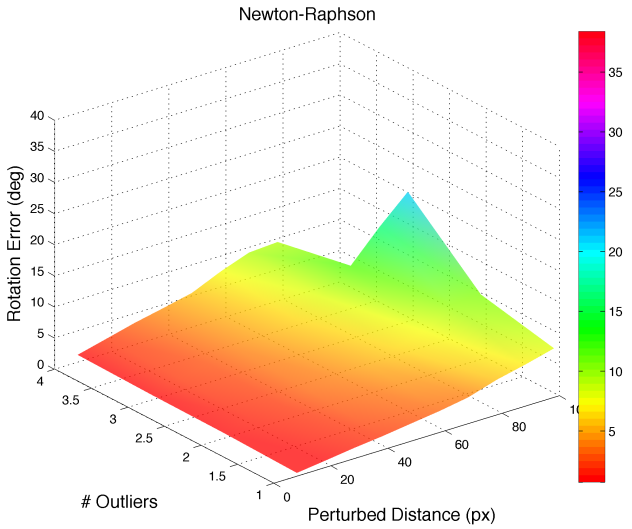

Epnp
Translation Error (%)
Outliers
Perturbed Distance (px)

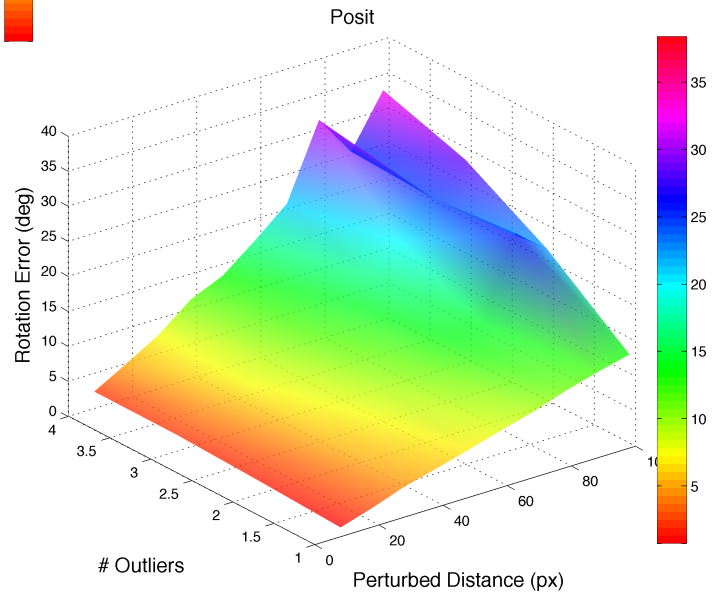

Newton-Raphson
Translation Error (%)
Perturbed Distance (px)


Posit
Translation Error (%)
Outliers
Perturbed Distance (px)

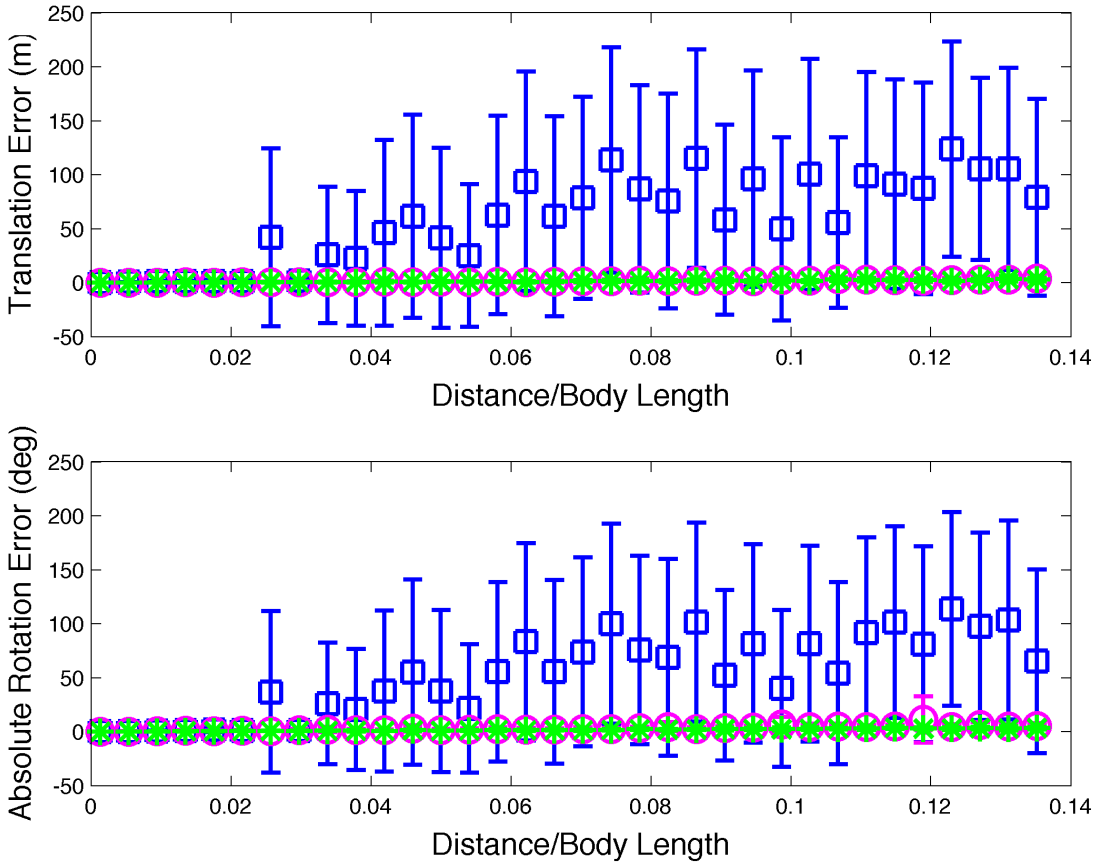
Outliers

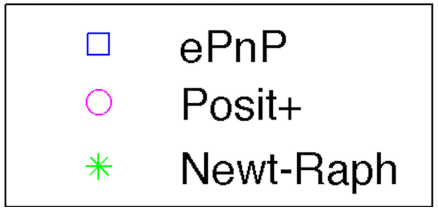

Epnp
Rotation Error (deg)
Outliers
Perturbed Distance (px)


Newton-Raphson
Rotation Error (deg)
Outliers
Perturbed Distance (px)


Posit
Rotation Error (deg)
Outliers
Perturbed Distance (px)

Distance along Optical Axis





Conclusions: Decision Matrix

	Number of Points	Noise	Outliers	Distance to Camera
Posit				
Epnp				
Posit+				
Newton Raphson				

Time (s)

Mean 2D Error (px)

Translation Error (%)

Rotation Error (deg)

Conclusions: Decision Matrix

	Number of Points	Noise	Outliers	Distance to Camera
Posit				
Epnp				
Posit+				
Newton Raphson				

Future Challenges

- Link with Model Matching (carrying multiple poses)
- Closed loop with image processing
- Explore synergy between different methods