Automatic Extrinsic Calibration for Lidar-Stereo Vehicle Sensor Setups

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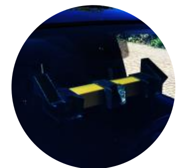
Agenda

Agenda

Perception systems in vehicles

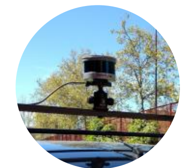
- Topologies with complementary sensory modalities

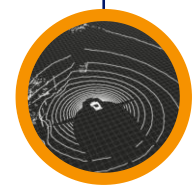
IVVI 2.0 Research Platform


Cameras


Stereo-vision systems

- Appearance information
- Cost-effective
- Dense 3D info.


Range scanners


Multi-layer 3D lidar scanner

- High accuracy
- 360º Field of View

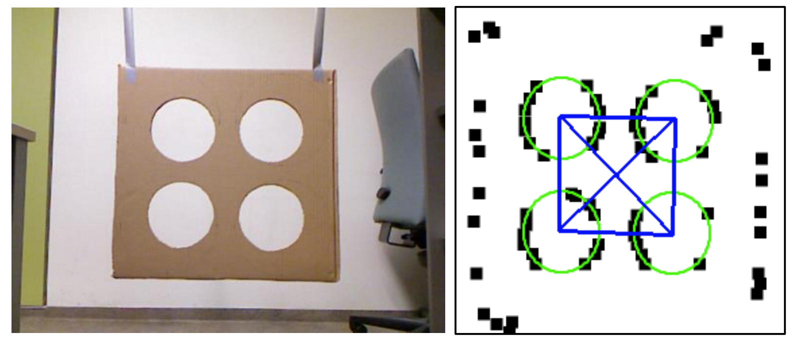
Data fusion

Ovelapping FOVs → Correspondence between data representations → Extrinsic calibration required

Previous works

- Camera-to-range calibration in robotic/automotive platforms
  - Complex setups / lack of generalization ability
  - Strong assumptions are usually made: sensor resolution, limited pose range, environment structure,…

Geiger et al., ICRA 2012



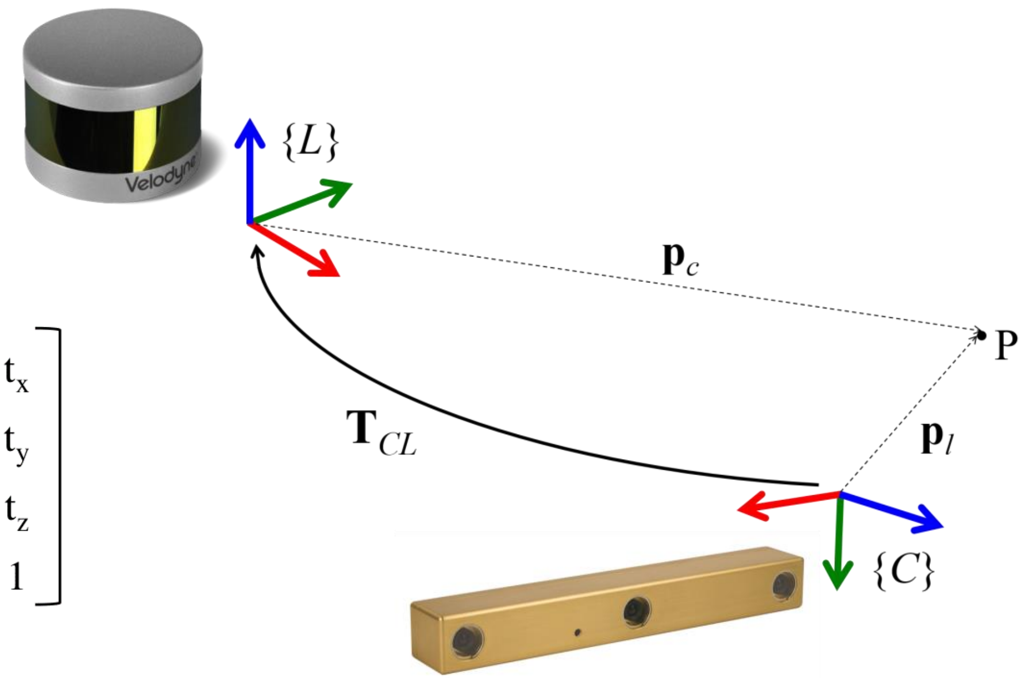
Velas et al., WSCG 2014

- Assessment of calibration methods
  - Ground-truth of extrinsic parameters cannot be obtained in practice

Levinson & Thrun, RSS 2013

Proposal overview

$$T_{CL} = \begin{bmatrix} r_{11} & r_{12} & r_{13} & t_x \\ r_{21} & r_{22} & r_{23} & t_y \\ r_{31} & r_{32} & r_{33} & t_z \\ 0 & 0 & 0 & 1 \end{bmatrix}$$



- Stereo-vision system–multi-layer lidar calibration
- Suitable for use with different models of lidar scanners (e.g. 16-layer)
- Very different relative poses are allowed
- Performed within a reasonable time using a simple setup

Agenda

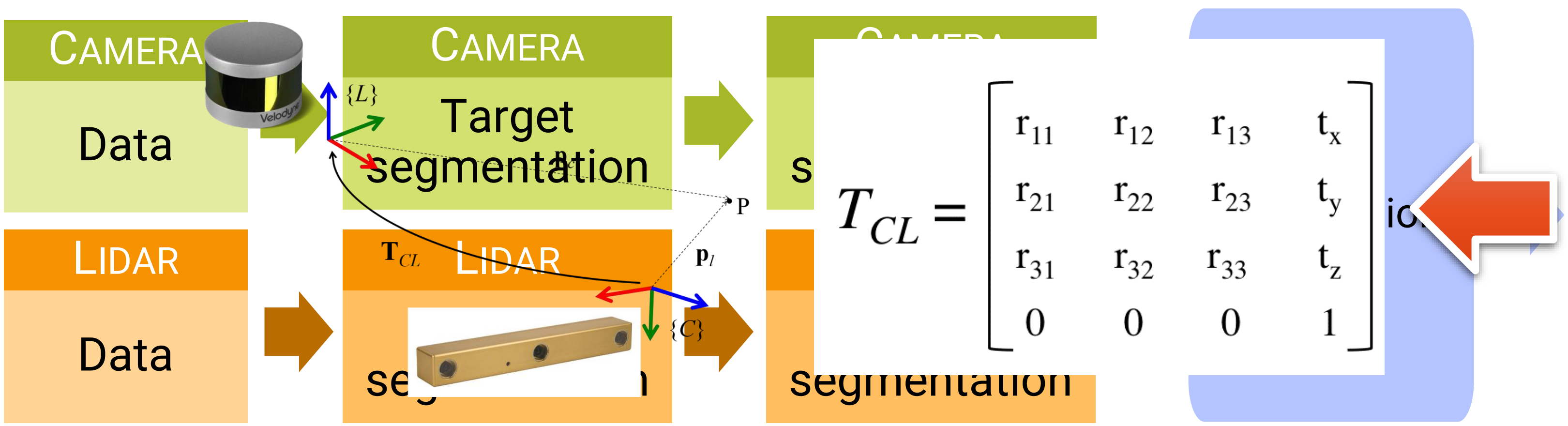
1. Motivation
2. Calibration algorithm
3. Synthetic test suite
4. Results
5. Conclusion

Calibration algorithm

- Calibration target

- Single point of view
- Holes visible from the camera and intersected by at least 2 lidar beams
- No alignment required

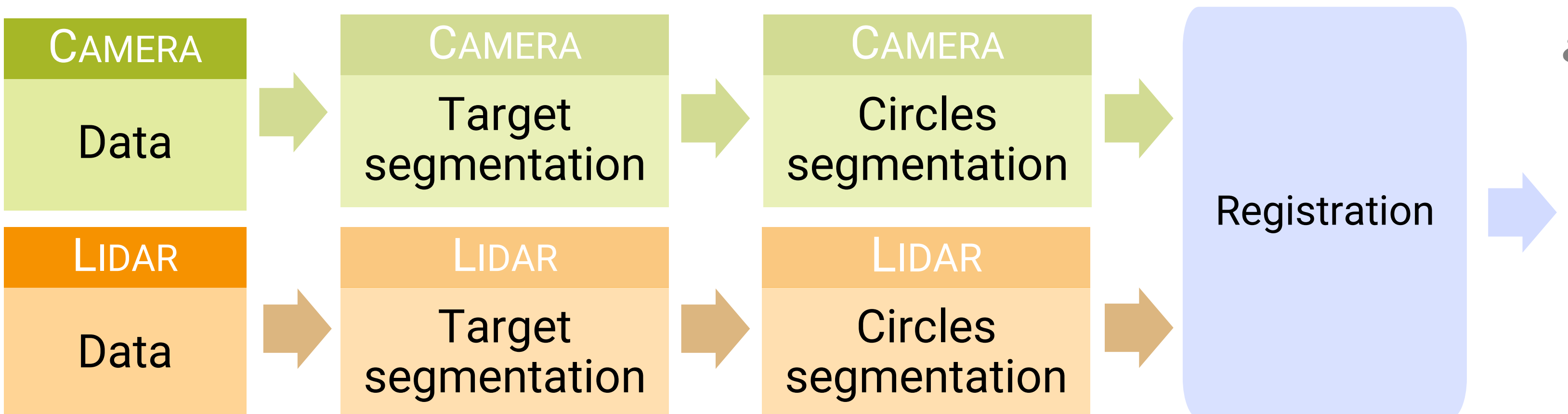
- Process overview



$$T_{CL} = \begin{bmatrix} r_{11} & r_{12} & r_{13} & t_x \\ r_{21} & r_{22} & r_{23} & t_y \\ r_{31} & r_{32} & r_{33} & t_z \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

$$\xi_{CL} = \begin{bmatrix} t_x \\ t_y \\ t_z \\ \phi \\ \theta \\ \psi \end{bmatrix}$$

Data representation



$$\xi_{\mathrm{CL}} = \begin{bmatrix} t_x \\ t_y \\ t_z \\ \phi \\ \theta \\ \psi \end{bmatrix}$$

Data representation

- 3D point clouds, $\mathcal{P}_0 = \{(x, y, z)\}$

CAMERA

Data

Left image

Right image

Stereo matching

Point cloud: $\mathcal{P}_0^c$

Stereo matching

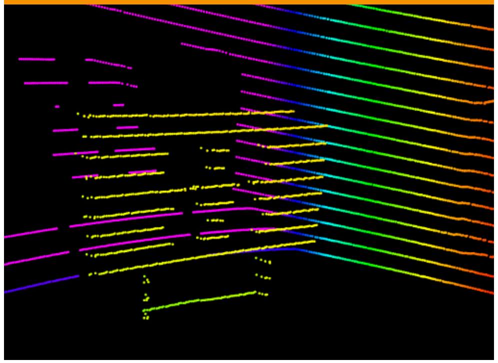
- Accuracy in the depth estimation is required (SGM)
- Border localization problem will be tackled using intensity

LIDAR

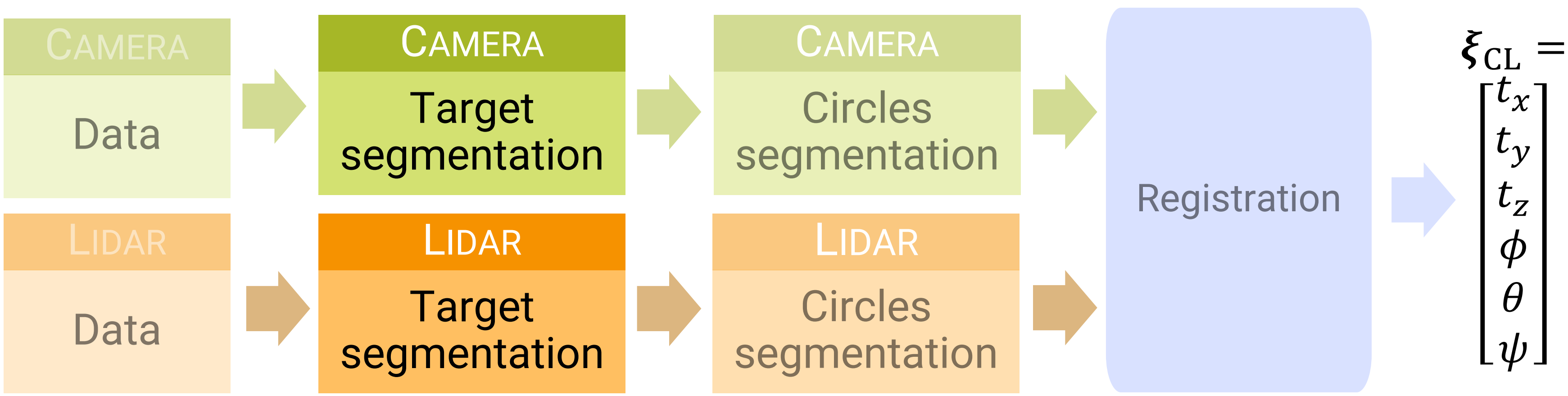
Data

Point cloud: $\mathcal{P}_0^l$

LIDAR: $\mathcal{P}_0^l$



Target segmentation · Step 1



Target segmentation · Step 1

- Extracting the points belonging to discontinuities in the target
- Successive segmentations: $\mathcal{P}_{i_0} = \{(x, y, z)\} \subseteq \mathcal{P}_{i_0 - 1}$

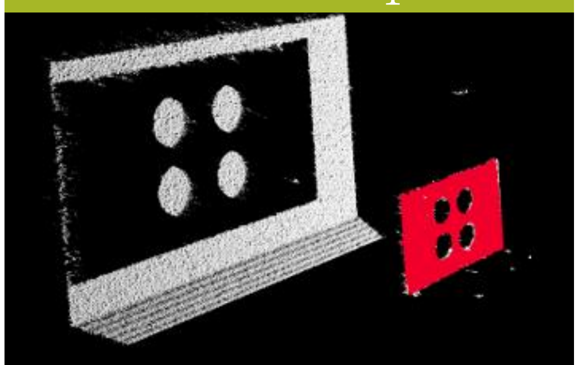
CAMERA/LIDAR
Target segmentation
Step 1

Point clouds: $\mathcal{P}_0$ → Plane model extraction → Remove pts. far from the planes

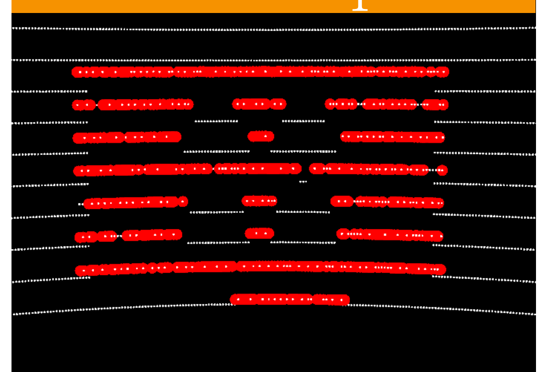
Plane model extraction

- Random sample consensus (RANSAC)
- Tight threshold (`1 cm`) and requirement for the plane to be roughly parallel to the vertical axis (`tol: 0.55 rad`)

CAMERA: $\mathcal{P}_1^c$

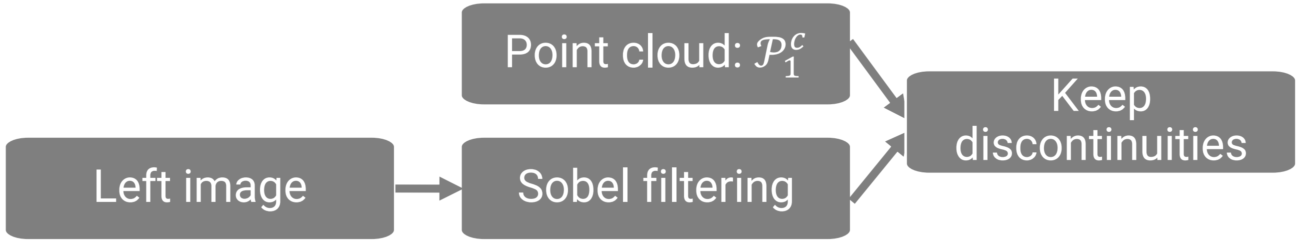


LIDAR: $\mathcal{P}_1^l$

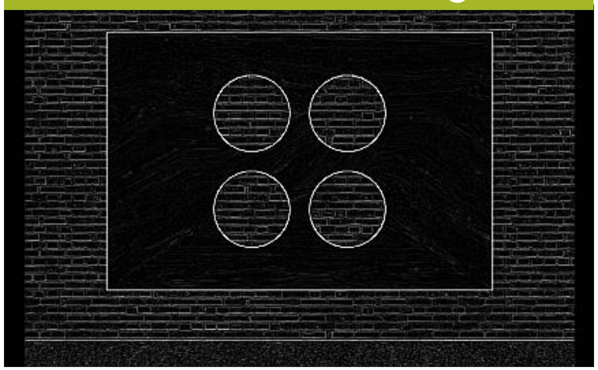


Target segmentation · Step 2

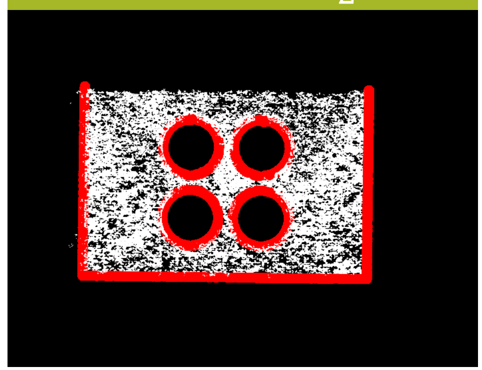
CAMERA
Target segmentation
Step 2



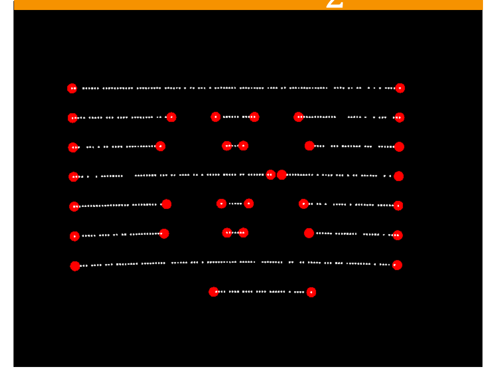
CAMERA: Sobel edges



CAMERA: $\mathcal{P}_2^c$



LIDAR: $\mathcal{P}_2^l$

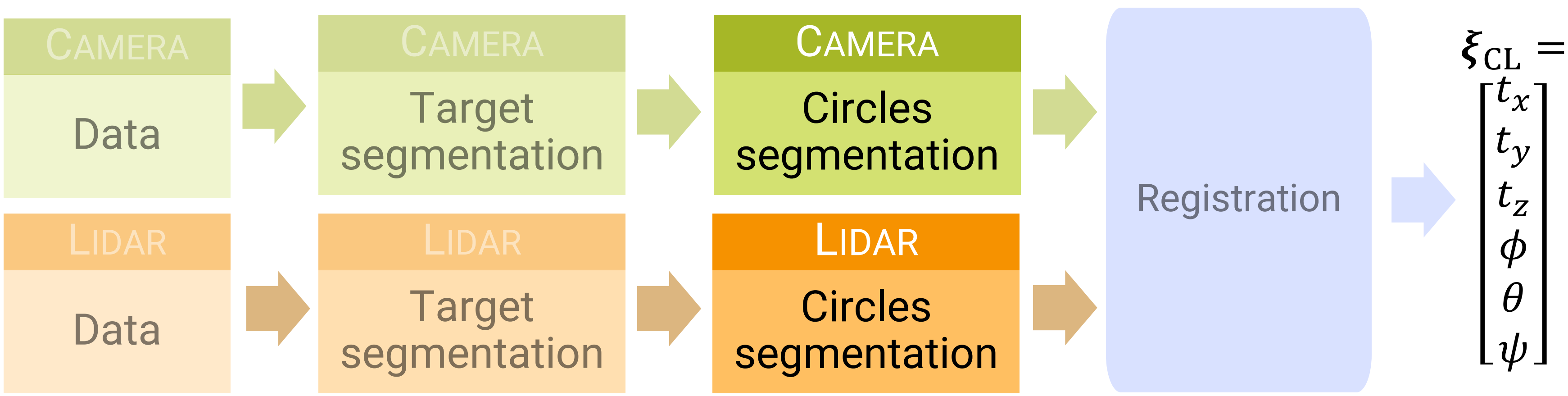


LIDAR
Target segmentation
Step 2

$p_\Delta^i = \max(p_r^{i-1} - p_r^i, p_r^{i+1} - p_r^i, 0)$ for every point in $\mathcal{P}_1^l$

Filter out $p_\Delta < \delta_{discont,l}$ `(50 cm)`

Circles segmentation · Step 1



Circles segmentation · Step 1

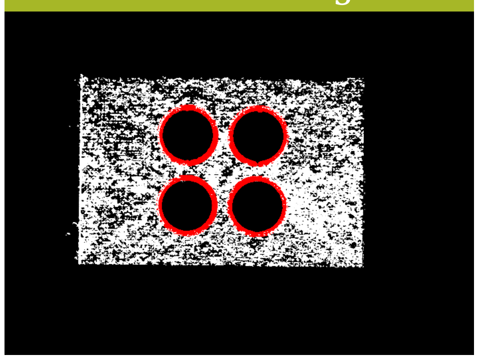
- Getting rid of the points not belonging to the circles: target boundaries

CAMERA
Circles segmentation
Step 1

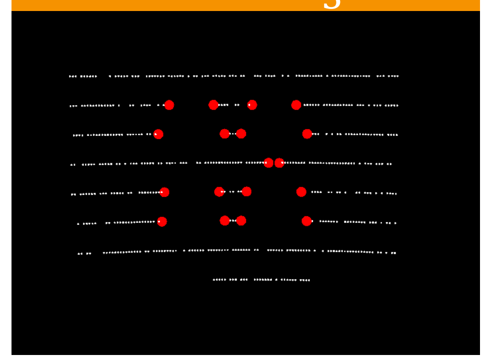
Point cloud: $\mathcal{P}_2^c$ → 3D-line RANSAC → Point cloud: $\mathcal{P}_3^c$

Geometrical constraints → 3D-line RANSAC

CAMERA: $\mathcal{P}_3^c$



LIDAR: $\mathcal{P}_3^l$



LIDAR
Circles segmentation
Step 1

- Keep only the rings where a circle is possible
- Remove the outer points

Circles segmentation · Step 2

- Detecting the center of the holes

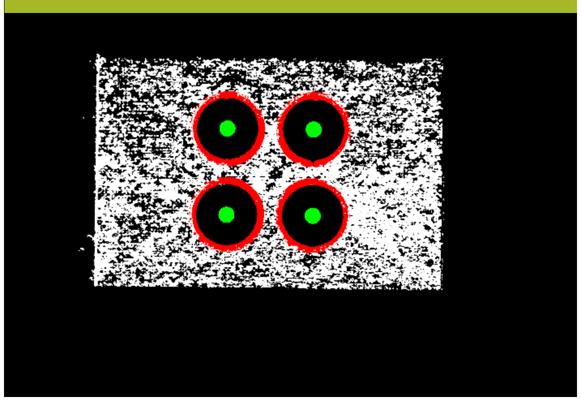
CAMERA/LIDAR
Circles segmentation
Step 2

Point cloud: $\mathcal{P}_3$ → Alignment with XY plane → 2D Circle RANSAC (← Geometrical constraints) → 4 x centers + radius → Undo the alignment → 4 x centers coordinates

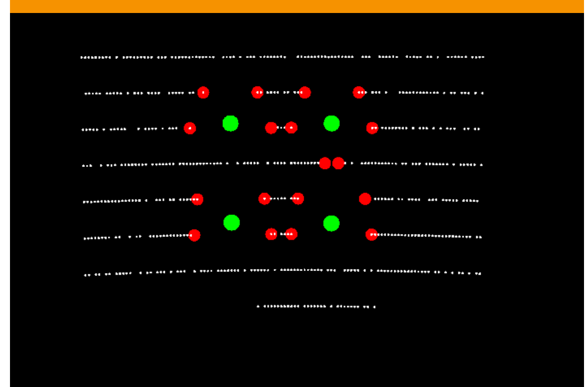
Circle model extraction

- 2D search: only three points are required

Camera



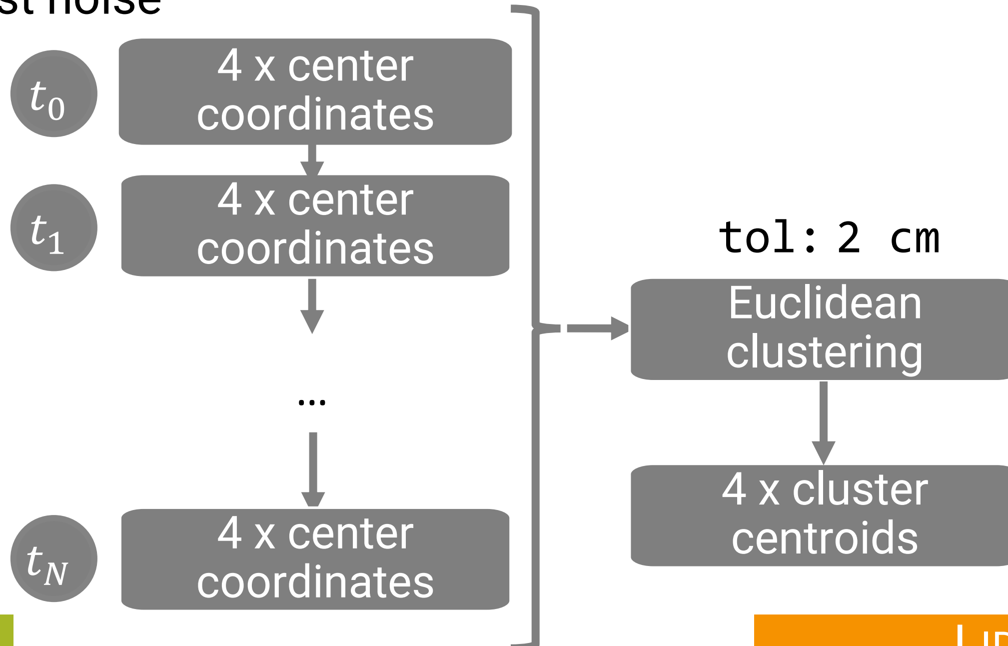
Lidar



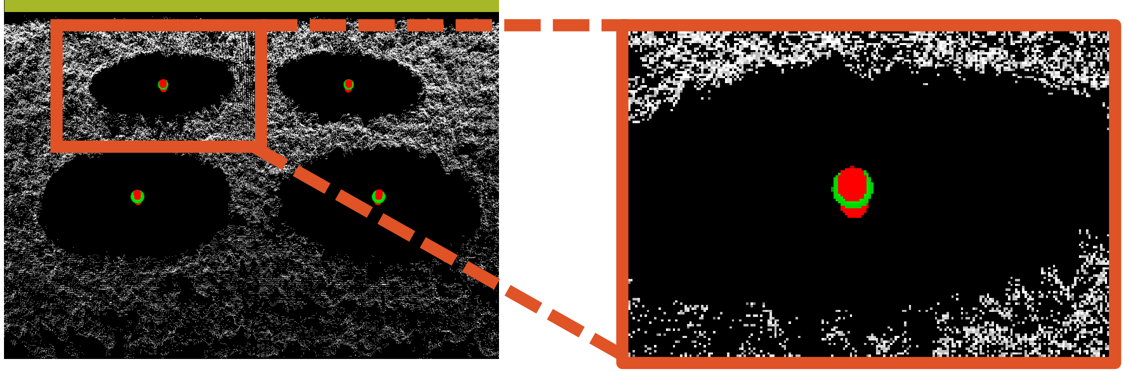
Circles segmentation · Step 3

- Robustness against noise

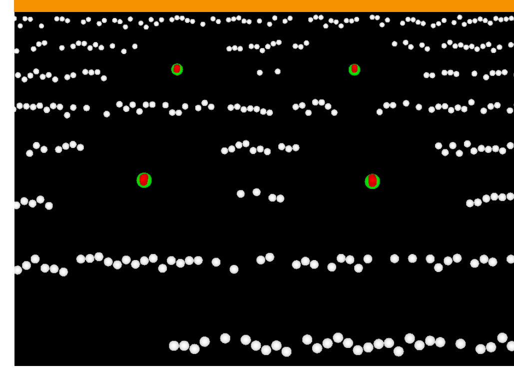
CAMERA/LIDAR
Circles segmentation
Step 3



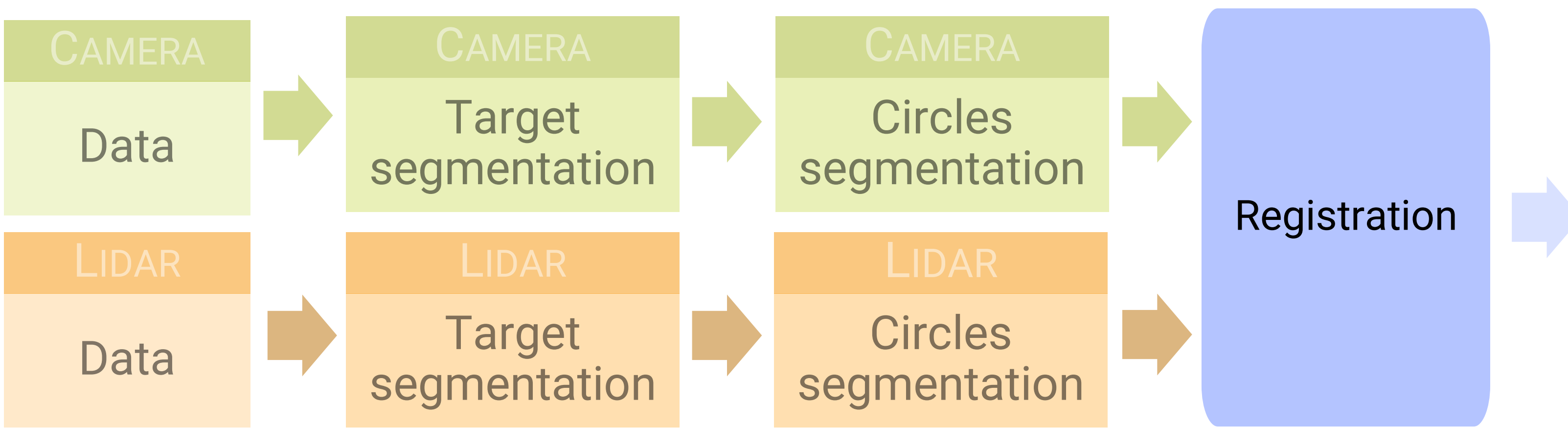
CAMERA



LIDAR

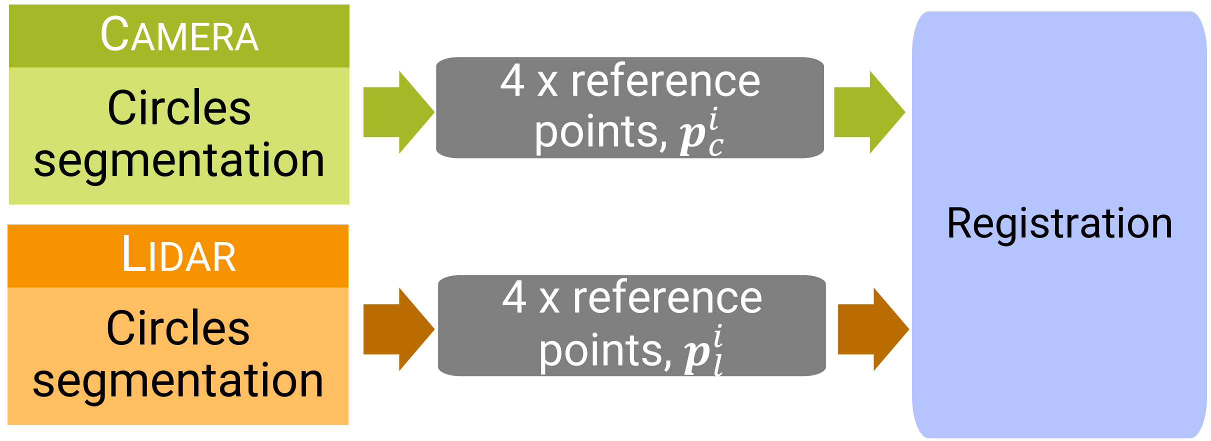


Registration



$$\xi_{\mathrm{CL}} = \begin{bmatrix} t_x \\ t_y \\ t_z \\ \phi \\ \theta \\ \psi \end{bmatrix}$$

Registration



Step 1

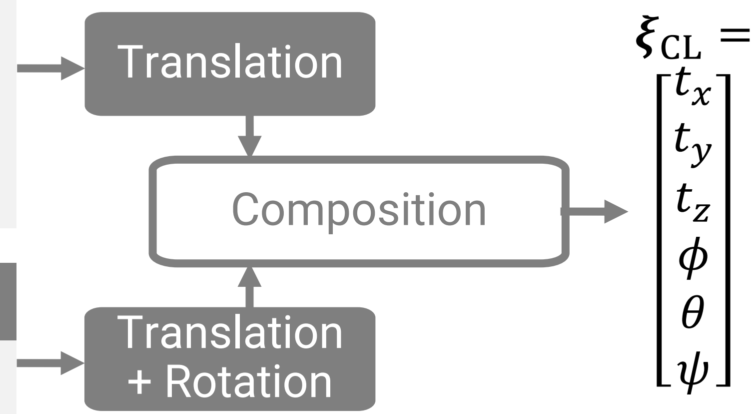
- Pure translation
- Overdetermined system of 12 equations

$$\boldsymbol{t}_{CL} = \overline{\boldsymbol{p}}_l^i - \overline{\boldsymbol{p}}_c^i$$

- Column-pivoting QR decomposition

Step 2

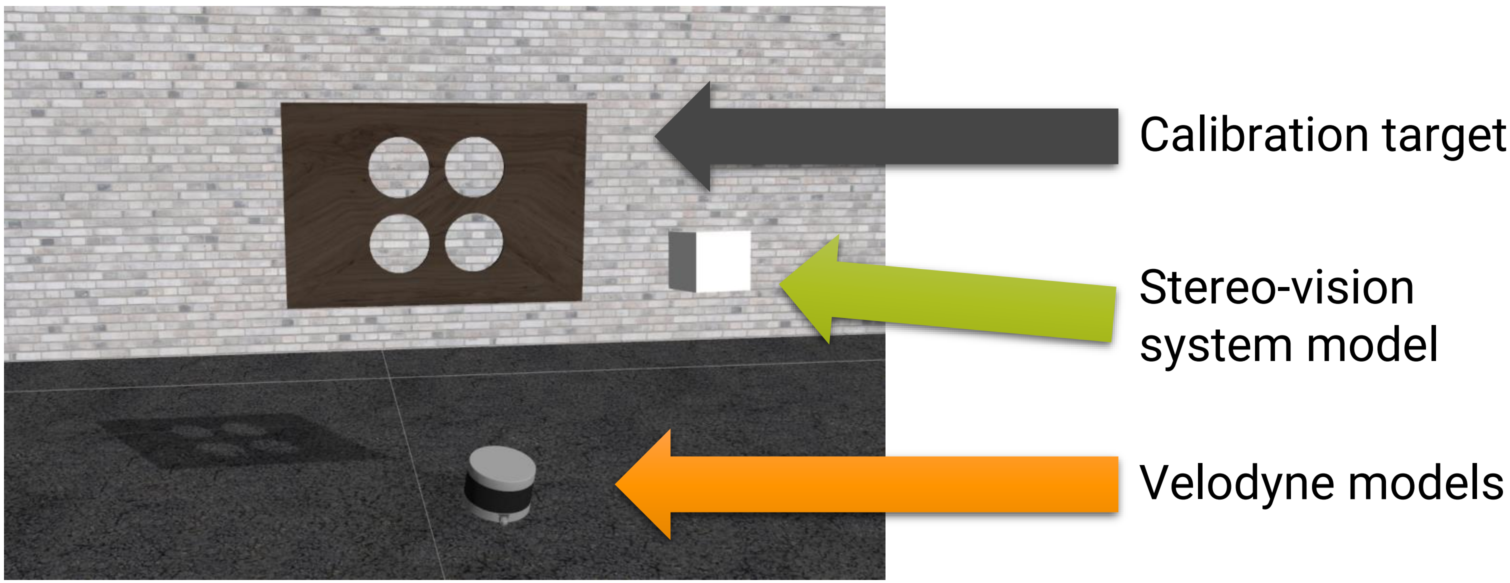
- Iterative Closest Points (ICP)



Agenda

Synthetic Test Suite

- Our proposal for quantitative assessment of calibration algorithms
- *Exact* ground-truth, but also noise and real constraints
- Simulation of sensors and their environment based on Gazebo
- Different calibration scenarios



Gazebo models, plugins and worlds available at
http://wiki.ros.org/**velo2cam_gazebo**
Open source · GPLv2 License

Agenda

Experimental setup

- Using the synthetic test suite
- Nine different calibration setups
  - 7 simple setups to evaluate the parameters of the transform
  - 2 challenging situations
- Gaussian noise added to the sensor measurements
- Models simulated with real parameters
  - 12 cm stereo baseline and 16-layer lidar

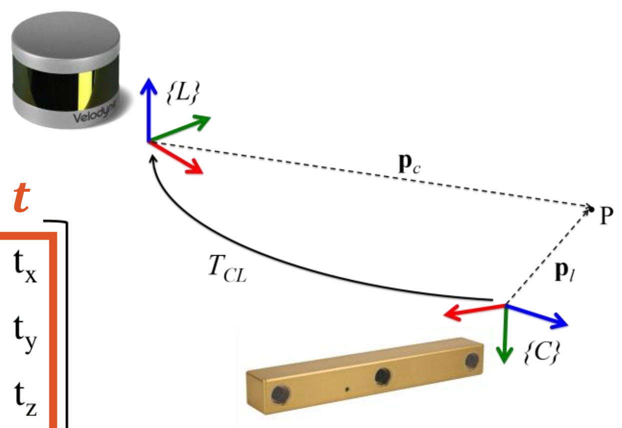
Translation error (linear)

$$e_t = \|\boldsymbol{t} - \boldsymbol{t}_g\|$$

Rotation error (angular)

$$e_r = \angle(\boldsymbol{R}^{-1}\boldsymbol{R}_g)$$

$$T_{CL} = \begin{array}{c} \qquad\qquad \boldsymbol{R} \qquad\qquad\quad \boldsymbol{t} \\ \begin{bmatrix} r_{11} & r_{12} & r_{13} & t_x \\ r_{21} & r_{22} & r_{23} & t_y \\ r_{31} & r_{32} & r_{33} & t_z \\ 0 & 0 & 0 & 1 \end{bmatrix} \end{array}$$



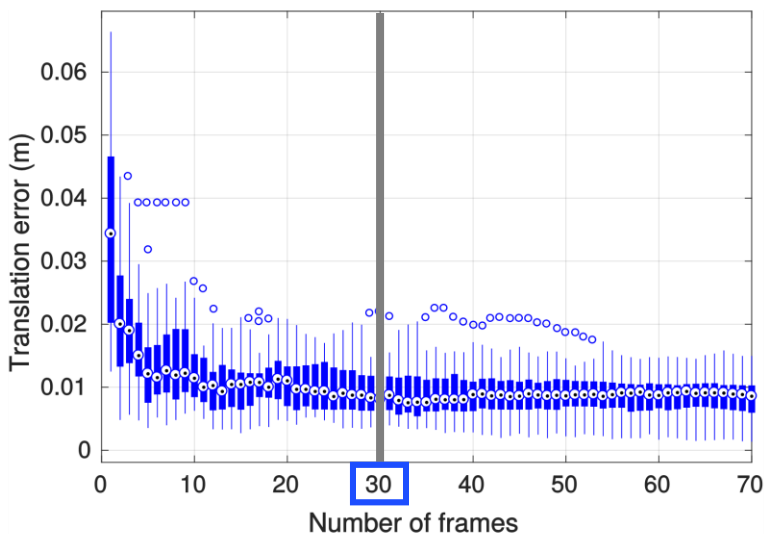
Experiments

CAMERA/LIDAR
Circles segmentation
Step 3

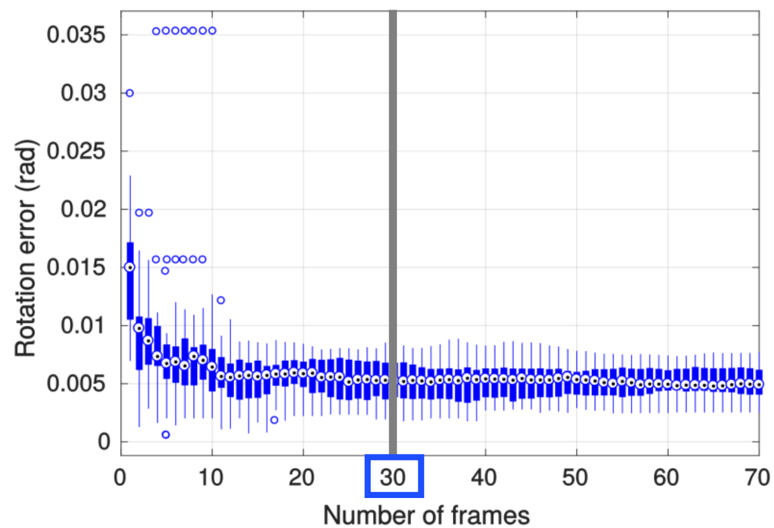
- Accumulation of cluster centroids over N frames
- N images and N point clouds processed
- Not every window provides clusters to be accumulated

Selection of the length of the window, N

Translation error (linear)



Rotation error (angular)



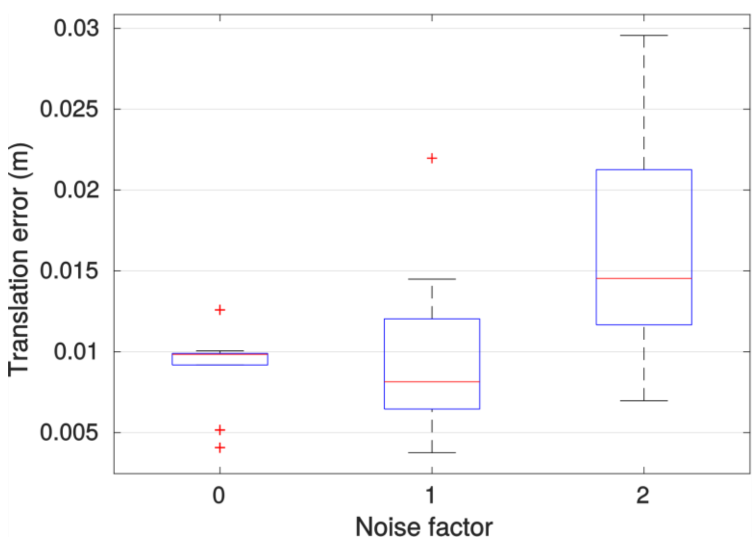
Experiments

- Noise is included in the measurements from the sensors
- Gaussian noise: $\mathcal{N}(0,(K\sigma_0)^2)$

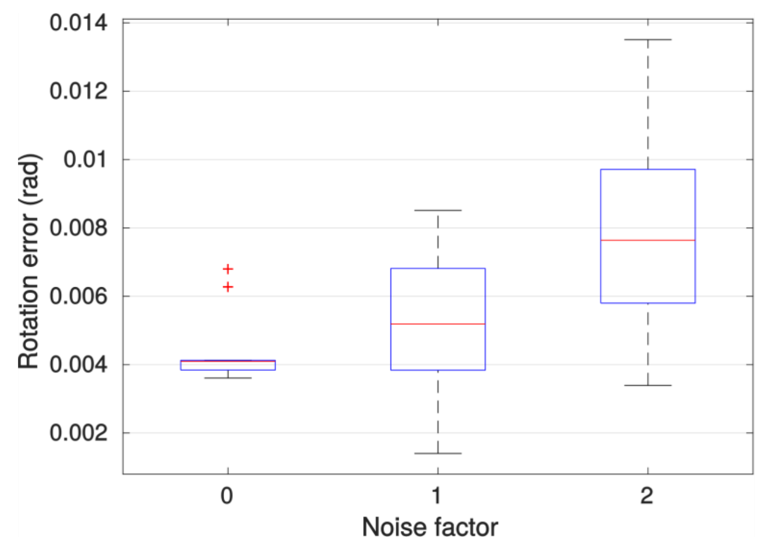
CAMERA	LIDAR
$\sigma_0^c = 0.007$	$\sigma_0^l = 0.008\ m$

Robustness to noise, K

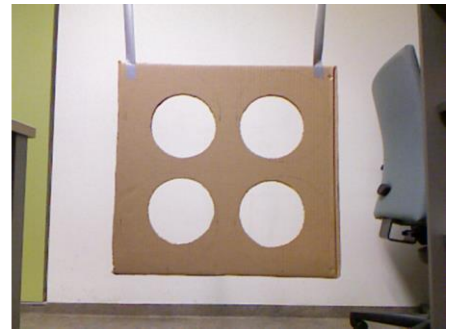
Translation error (linear)

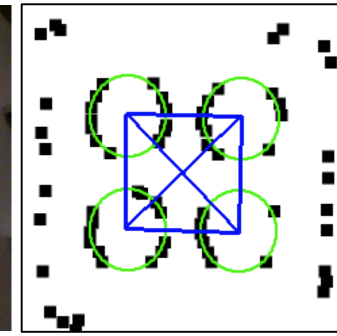


Rotation error (angular)



Comparison

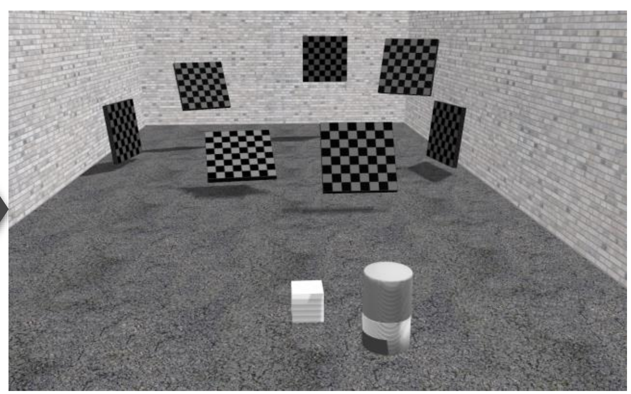




Geiger et al., ICRA 2012

- Public web toolbox
- **Monocular** cam., provide intrinsics
- Tested with HDL-64E & Kinect

Recreated In Gazebo



Velas et al., WSCG 2014

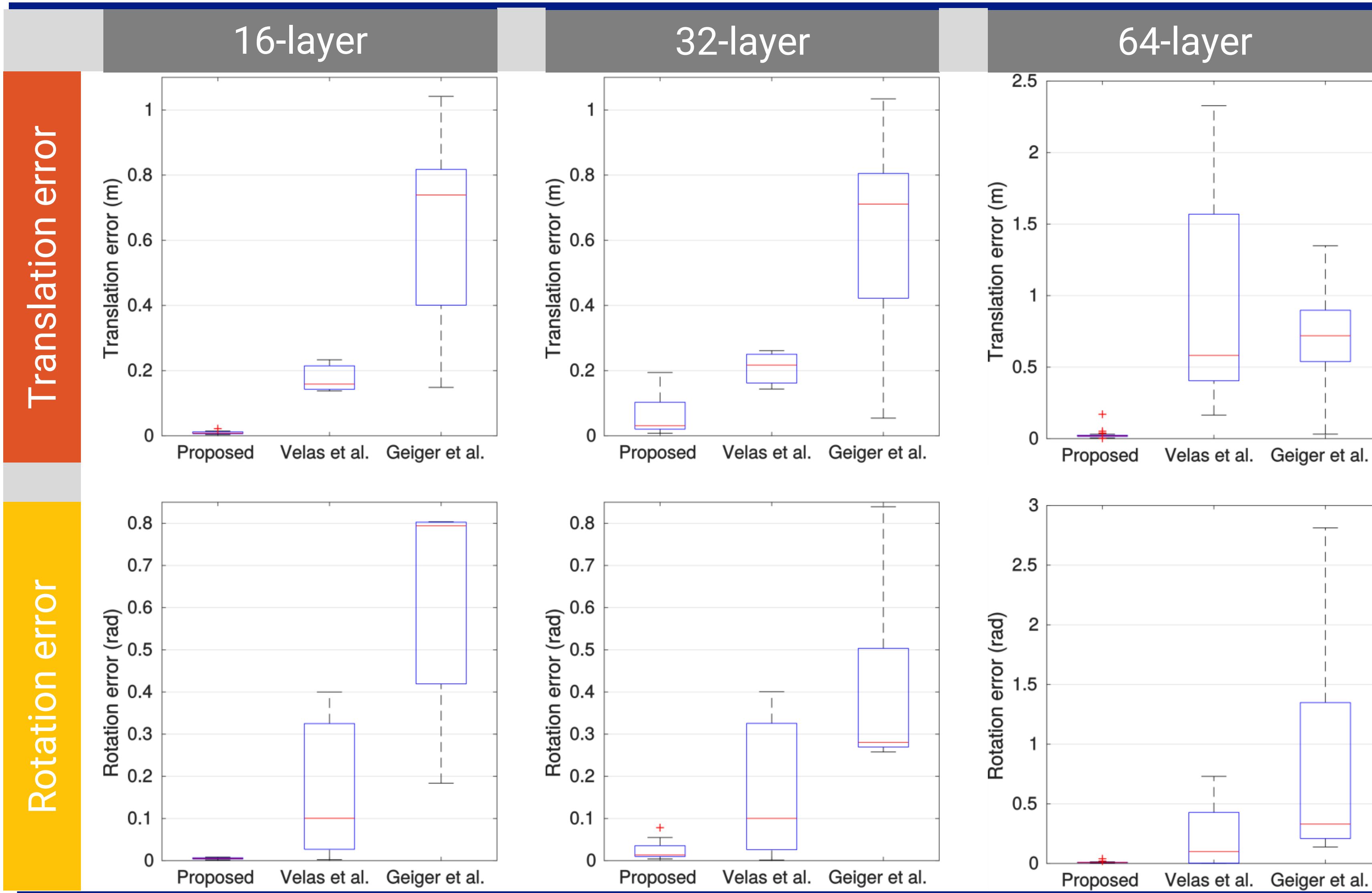
- Public ROS package
- **Monocular** camera
- Not suitable for large pose displacements
- Tested with HDL-32E

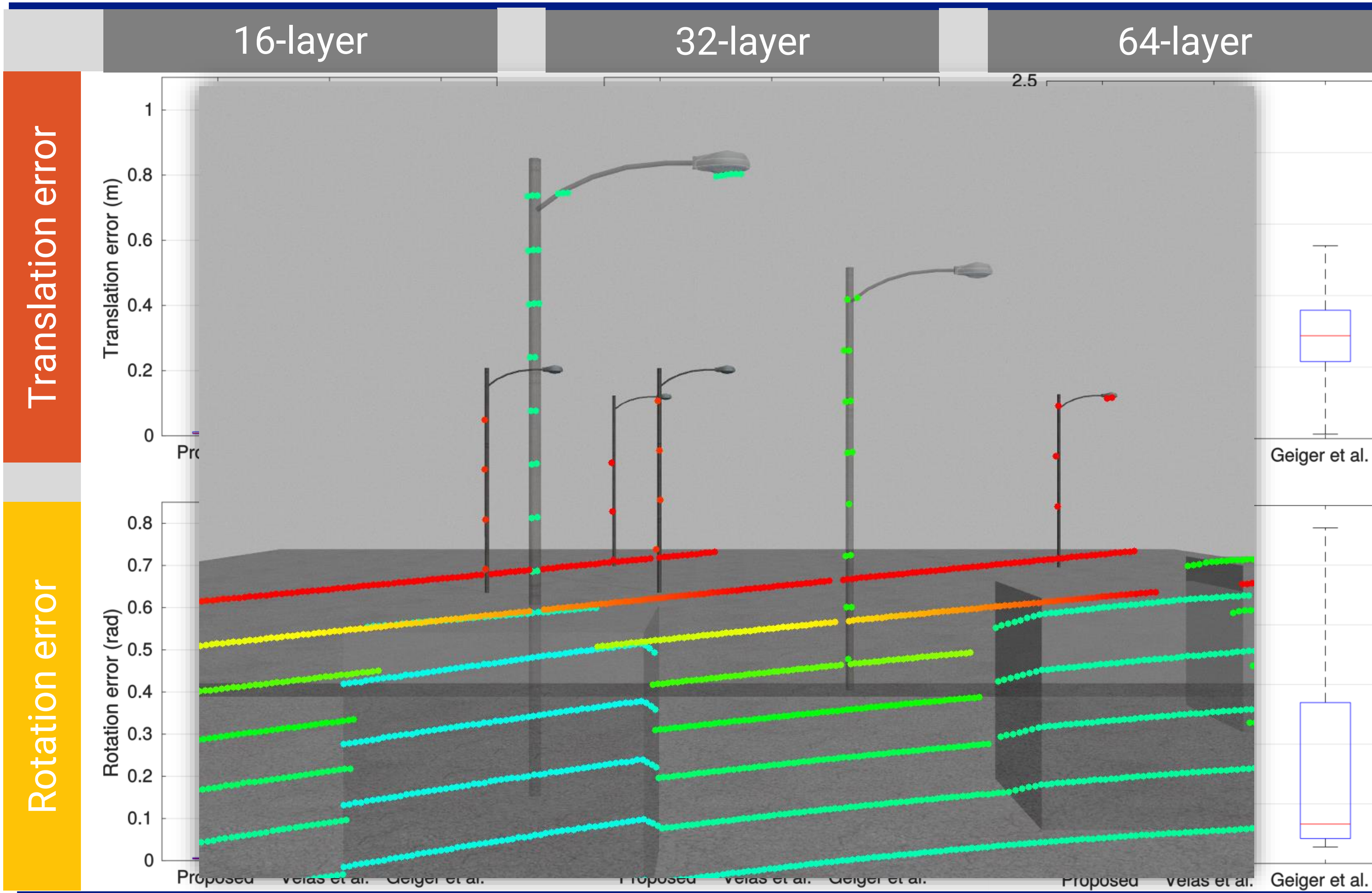
16 layers

32 layers

64 layers

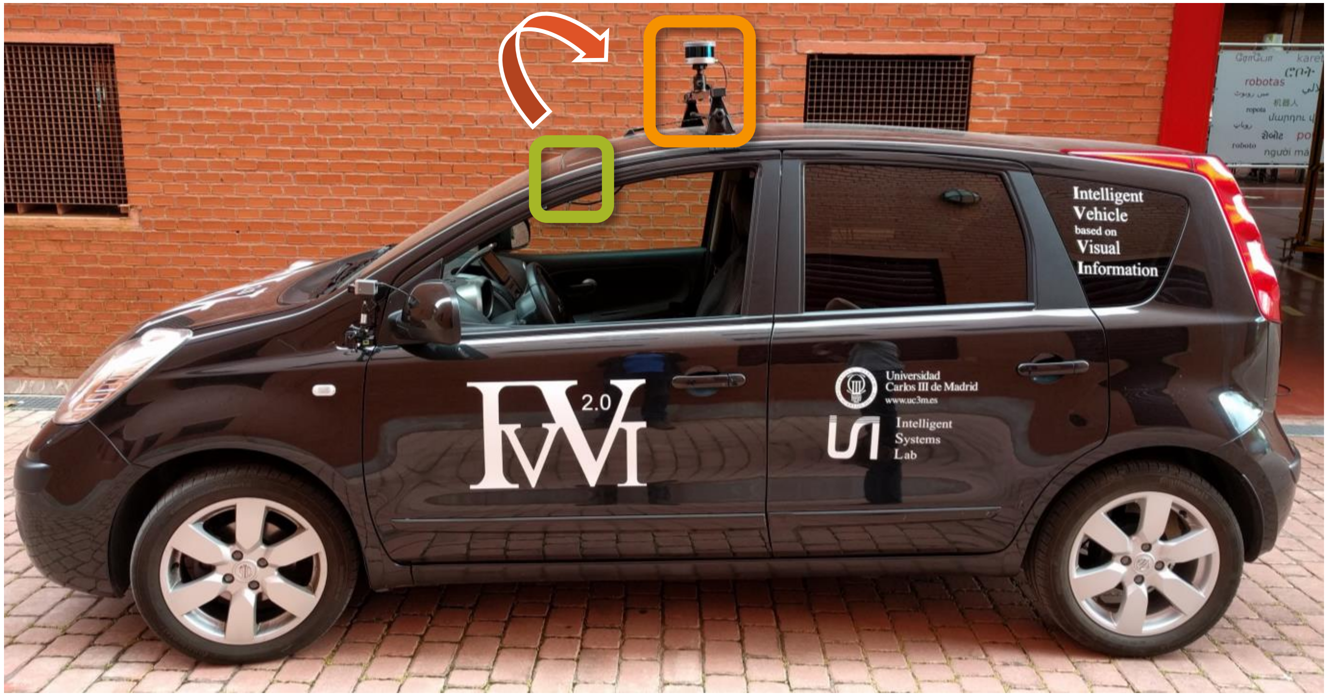
Experiments

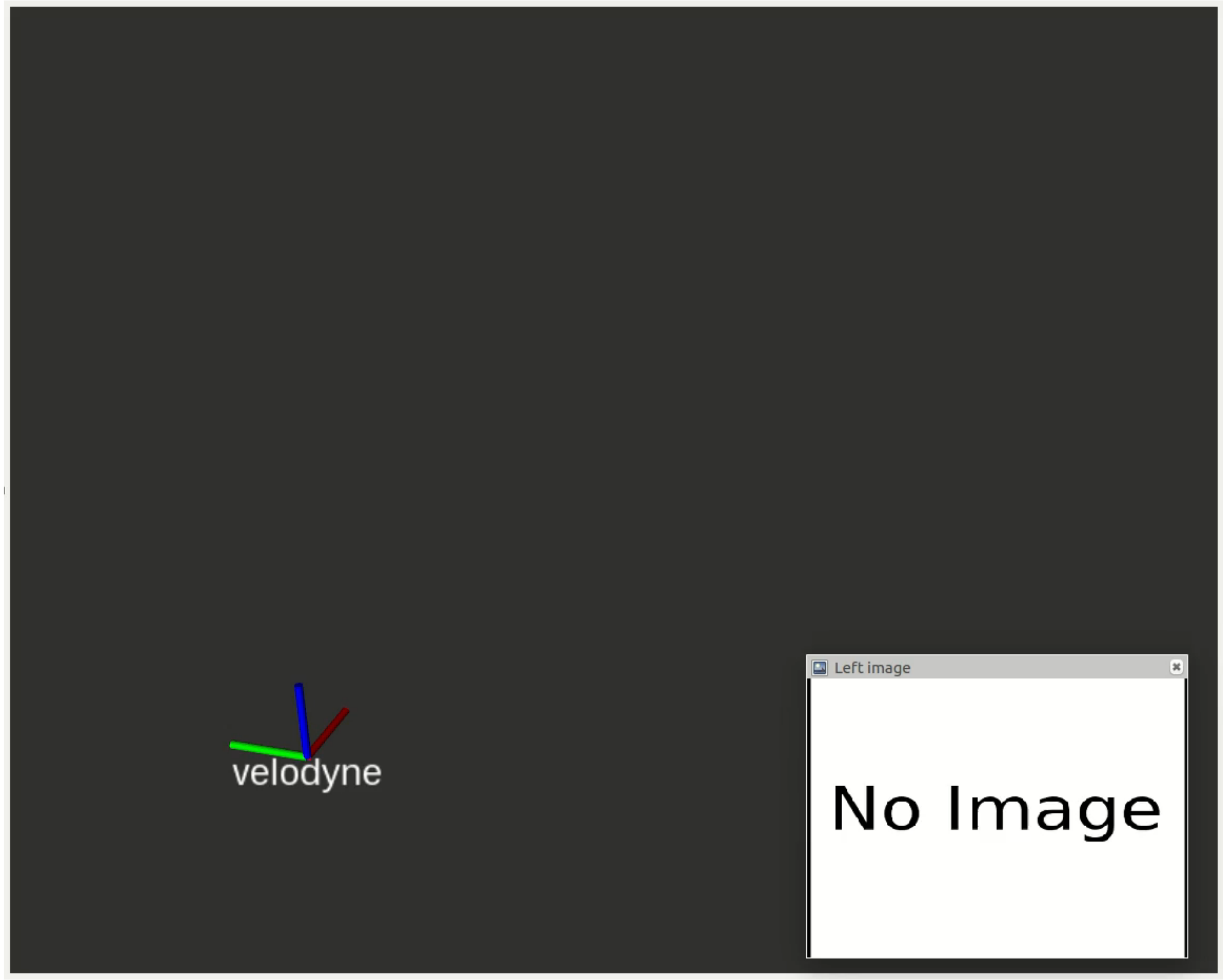



16-layer
32-layer
64-layer
Translation error
Rotation error
Translation error (m)
Rotation error (rad)
Geiger et al.
Proposed
Velas et al.
Geiger et al.
2.5

Results

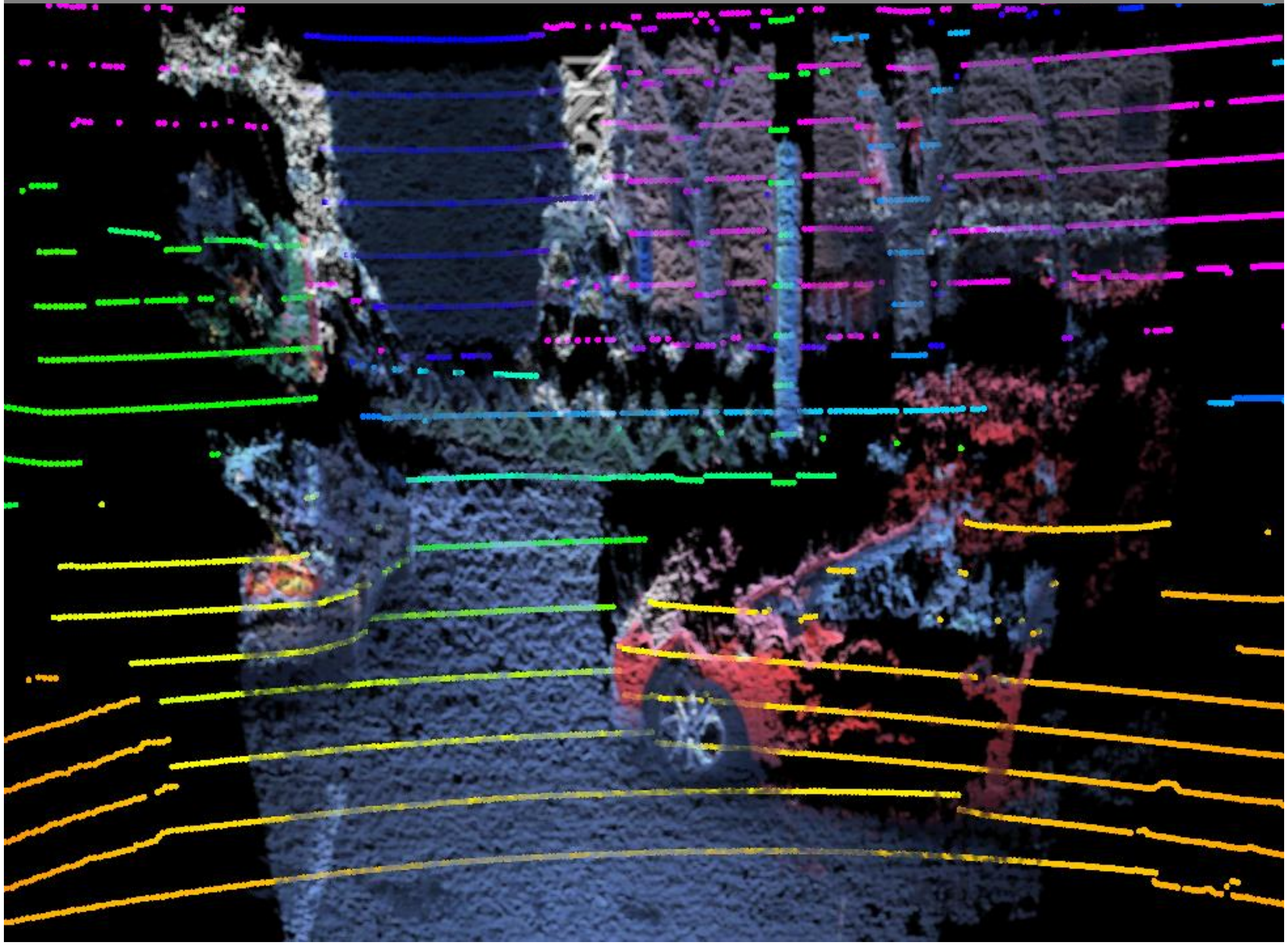
- IVVI 2.0 platform
  - Bumblebee XB3 stereo system: 1280 x 960 images, 12 cm baseline
  - Velodyne VLP-16




velodyne
Left image
No Image

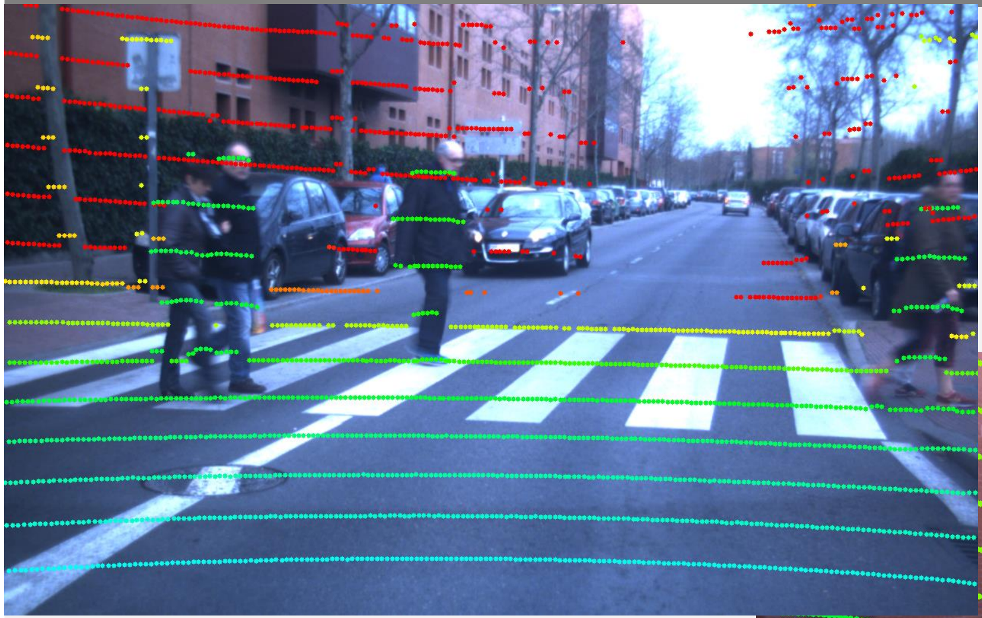
Results in real scenarios

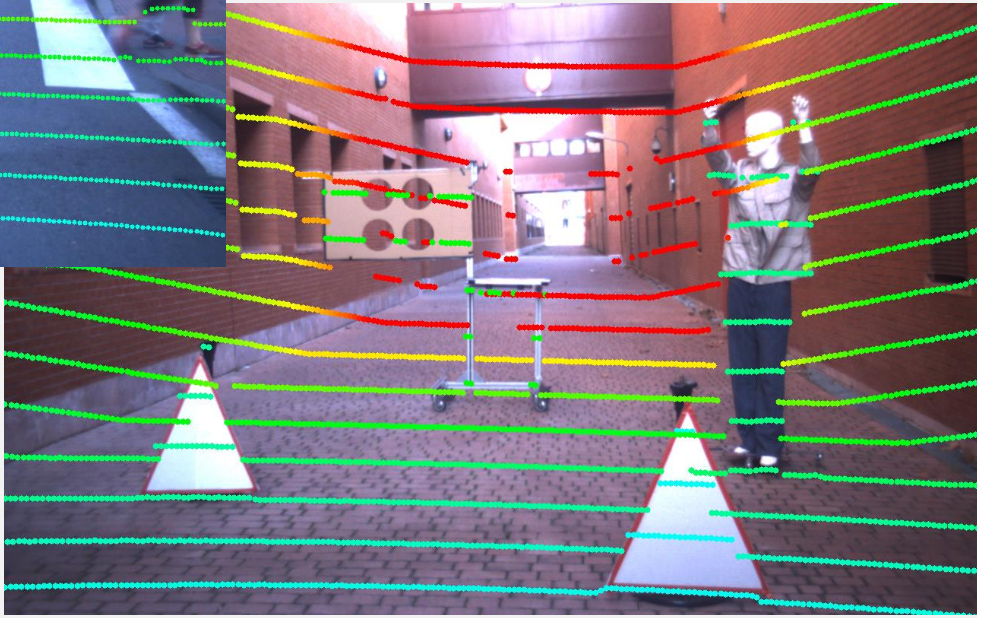
Stereo + lidar point clouds aligned



Results in real scenarios

Lidar measurements projected on the image





Agenda

Conclusion

- Method for calibration of lidar–stereo-camera setups:
  - Without user intervention
  - Suitable for close-to-production devices
- Assessment of the calibration methods using advanced simulation
  - Exact ground-truth in unlimited calibration scenarios
- Results validate our calibration approach

Future work

- Further testing
  - Sensitivity to different stereo matching approaches (e.g. CNN-based), weather/illumination conditions,…
- Monocular camera–multi-layer lidar calibration
  - Geometrical information may be extracted from the calibration target

ROS Package available at
http://wiki.ros.org/**velo2cam_calibration**
Open source · GPLv2 License

Thank you for your attention

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Yokohama · 17 October 2017