Final Presentation Master Thesis

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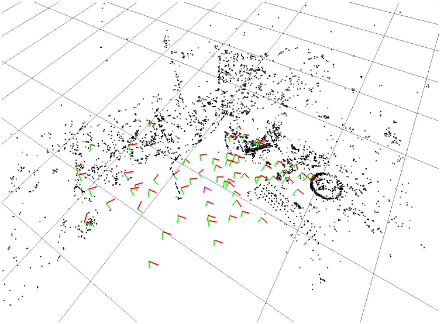
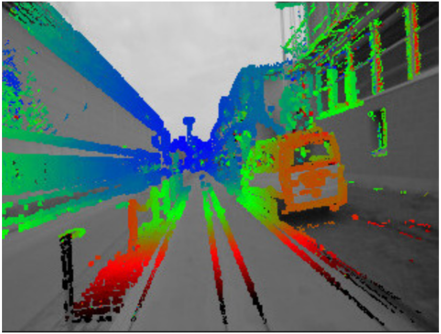
Outline

Dense SLAM with B-Splines
Motivation



(a) Sparse SLAM (PTAM, [?])



(b) Dense SLAM (LSD-SLAM, [?])

Stereo Surface Reconstruction And Localization

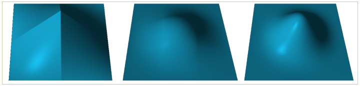
Project Goals

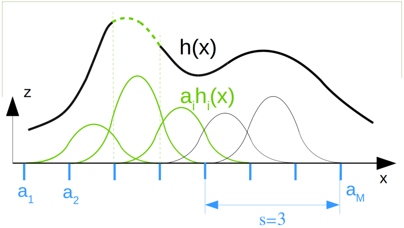
Create framework for surface reconstruction and localization using moving stereo camera.

- *Added functionalities*
  - Create spline surface reprensentation from static stereo camera.
  - Localize new stereo camera position using obtained map.
- *Methodology*
  - **Simulation environment**: `ROS` with `rviz` for pointcloud and `opencv` for image handling.
  - **Optimization**: own implementation of optimization algorithm using `Eigen` 's sparse matrix solvers.
  - **Hardware**: stereo camera data from `rovio` sensor, *MacBook Pro* with Intel Core 2.7MHz, 4 cores.

B-Splines for Surface Representation
Theoretical Concepts

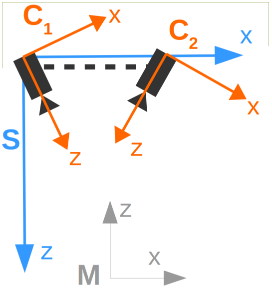
Splines: piecewise polynomial function of degree $<d$. *B(asis)-Splines*: Specific choice of finite-support splines calculated by *Cox de Boor* recursion formula (support $s = d + 1$).





$$h(x_j) = \sum_{i=0}^{M} a_i h_i(x_j)$$
$$= \sum_{i=k}^{k+s} a_i h_i(x_j), \text{ for } j = 1 \dots N$$

Stereo Camera Setup
Theoretical Concepts



Camera poses described by ${}_M\boldsymbol{r}_{MC_k}$ and $\boldsymbol{C}_{C_k M}$ for $k = 1, 2$ or

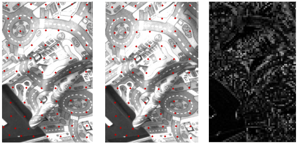
$$\xi_{C_k} := \left[{}_M\boldsymbol{r}_{MC_k}, \boldsymbol{\Phi}_{\boldsymbol{CM}}\right]^T$$

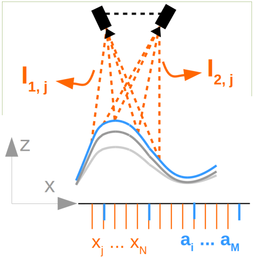
$$\xi_S := \left[{}_M\boldsymbol{r}_{MS}, \boldsymbol{\Phi}_{\boldsymbol{SM}}\right]^T$$

with $\boldsymbol{\Phi}_{\boldsymbol{CM}}$, $\boldsymbol{\Phi}_{\boldsymbol{SM}} \in \mathbb{R}^3$ [?]

If stereo rotation matrices $\boldsymbol{R}_k := \boldsymbol{C}_{SC}$ and baseline $\boldsymbol{T}_x := {}_S\boldsymbol{r}_{C_1 C_2}$ are known, one pose of $\{\xi_{C_1}, \xi_{C_2}, \xi_S\}$ is sufficient for all poses to be defined.

Photometric errors for mapping
Theoretical Concepts





Photometric error of grid point x_j, y_j:

$$r_j = I_1(\boldsymbol{u}_{j,1}) - I_2(\boldsymbol{u}_{j,2}) \ ,$$

with I_1, I_2 interpolated intensities at the locations $\boldsymbol{u}_{j,k}$ in camera $k = 1$ and $k = 2$.

$$\boldsymbol{u}_{j,k} = \boldsymbol{K}_k D_k(\boldsymbol{T}_k({}_M\boldsymbol{r}_{MX_j}))$$

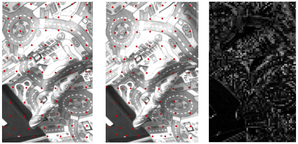
$$\boldsymbol{T}_k({}_M\boldsymbol{r}_{MX_j}) = \pi(\boldsymbol{C}_{C_k M}({}_M\boldsymbol{r}_{MX_j} - {}_M\,\boldsymbol{r}_{MC_k}))$$

3D point given by spline map:

$${}_M\boldsymbol{r}_{MX_j} = \left[x_j, y_j, h(x_j, y_j)\right]^T$$

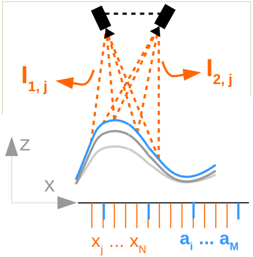
Photometric errors for mapping

Theoretical Concepts



$$J_r(\boldsymbol{a}) = \frac{\partial \boldsymbol{r}(\boldsymbol{a})}{\partial \boldsymbol{a}} \in \mathbb{R}^{NxM}$$

$$\begin{aligned} J_r(\boldsymbol{a}) = \big(& J_{pixel,1} J_{camera,1}({}_M\boldsymbol{r}_{MX_j}) \\ &- J_{pixel,2} J_{camera,2}({}_M\boldsymbol{r}_{MX_j})\big) J_{splines} \ . \end{aligned}$$



$$J_{pixel,k} = \frac{\partial I_k(\boldsymbol{u}_k)}{\partial \tilde{\boldsymbol{u}}_k}, \quad J_{camera,k}({}_M\boldsymbol{r}_{MX_j}) = \frac{\partial \tilde{\boldsymbol{u}}_k}{\partial {}_M\boldsymbol{r}_{MX_j}}$$

$$J_{splines} = \frac{\partial {}_M\boldsymbol{r}_{MX_j}}{\partial \boldsymbol{a}}$$

Optimization problem for mapping

Theoretical Concepts

$$\hat{\boldsymbol{a}} = \underset{\boldsymbol{a}\in\mathbb{R}^M}{\arg\min}\ f(\boldsymbol{a}) = \underset{\boldsymbol{a}\in\mathbb{R}^M}{\arg\min}\ \frac{1}{2}\Big(\sum_{j=0}^{N} w_j r_j(\boldsymbol{a})^2 + \beta \boldsymbol{a}^T \boldsymbol{B}\boldsymbol{a} + \gamma \boldsymbol{a}^T \boldsymbol{G}\boldsymbol{a}\Big)\ ,$$

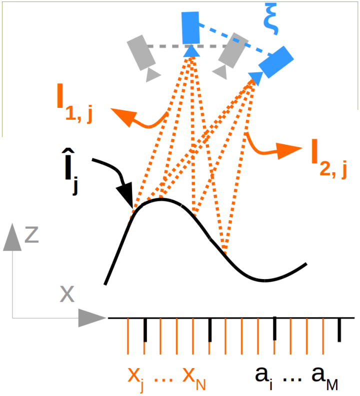
with

- bending and gradient energy regularization terms and
- weight representing the average visibility of point j.

Solved using Gauss-Newton iterations:

$$\boldsymbol{a}_{k+1} = \boldsymbol{a}_k + \alpha_k \mathbf{p}_k^{GN}$$
$$\boldsymbol{J}_f(\boldsymbol{a})^T \boldsymbol{J}_f(\boldsymbol{a})\mathbf{p}_k^{GN} = -\ \boldsymbol{J}_f(\boldsymbol{a})^T \mathbf{r}_k(\boldsymbol{a})$$

Photometric errors for localization
Theoretical Concepts

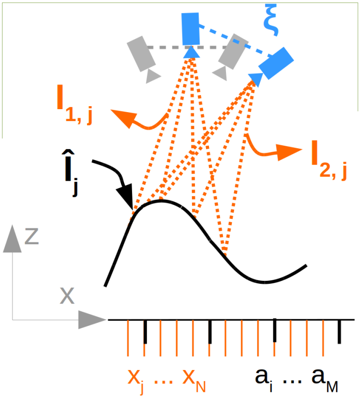


Photometric error of grid point x_j, y_j:

$$r_{j,1} = I_1(\boldsymbol{u}_{j,1}) - \hat{I}(x_j, y_j)$$
$$r_{j,2} = I_2(\boldsymbol{u}_{j,1}) - \hat{I}(x_j, y_j) \ ,$$

with I_1, I_2 interpolated intensities at pixels $\boldsymbol{u}_{j,k}$ in camera $k = 1$ and $k = 2$ and $\hat{I}(x_j, y_j)$ the estimated intensity from previous step.

Photometric errors for localization
Theoretical Concepts



$$J_r(\xi) = \frac{\partial \boldsymbol{r}(\xi)}{\partial \xi} \in \mathbb{R}^{Nx6}$$

$$J_r(\xi) = J_{pixel} J_{camera}(\xi)$$

with

$$J_{pixel} = \frac{\partial I(\boldsymbol{u})}{\partial \tilde{\boldsymbol{u}}}, \quad J_{camera}(\xi) = \frac{\partial \tilde{\boldsymbol{u}}}{\partial \xi}$$

Optimization problem for localization

Theoretical Concepts

$$\hat{\boldsymbol{\xi}} = \underset{\hat{\boldsymbol{\xi}} \in \mathbb{R}^6}{\arg\min} \; \frac{1}{2} \sum_{j=0}^{N} r_j(\boldsymbol{\xi})^2$$

Solved using Gauss-Newton iterations:

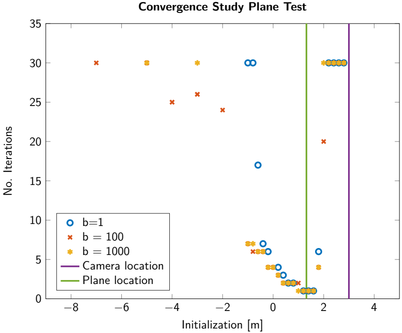
$$\begin{aligned} \boldsymbol{\xi}_{k+1} &= \boldsymbol{\xi}_k \boxplus \alpha_k \mathbf{p}_k^{GN} \\ \boldsymbol{J}_r(\boldsymbol{\xi})^T \boldsymbol{J}_r(\boldsymbol{\xi}) \mathbf{p}_k^{GN} &= - \boldsymbol{J}_r(\boldsymbol{\xi})^T \mathbf{r}_k(\boldsymbol{\xi}) \end{aligned}$$

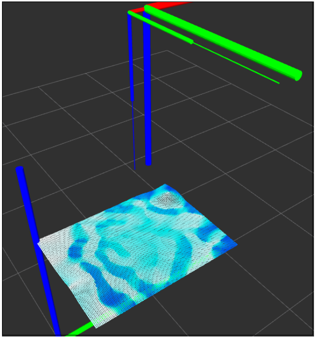
Datasets and parameters

Theoretical Concepts

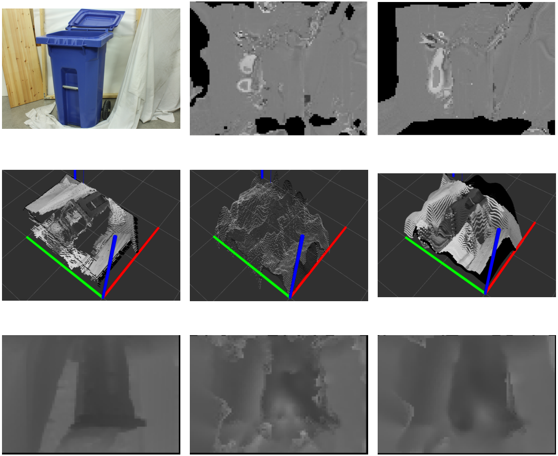
Dataset	Plane test	Middlebury [?]	Inhouse
Ground truth	analytical	structured light	pattern matching
Images	rectified	rectified	non rectified
Calibration	+++	++	+
Mapping	yes	yes	yes
Localization	yes	no	no
Spline resolution	20 x 20	75 x 100	
Map dimensions	0.9 x 1.2	1.5 x 2.0	
Map resolution	90 x 120		

Plane test case
Mapping

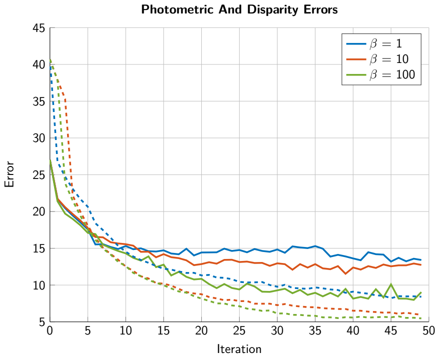


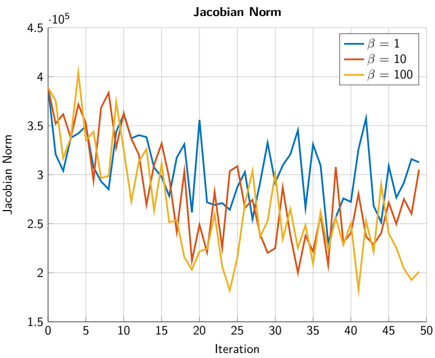


Middlebury dataset results
Mapping



Middlebury dataset convergence
Mapping

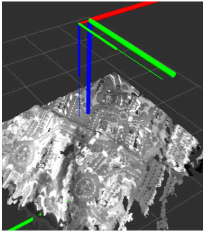
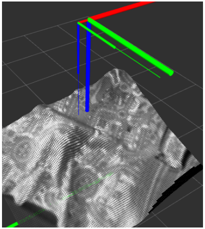
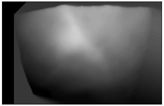
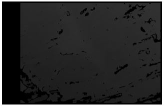




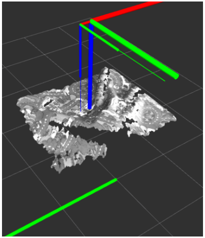
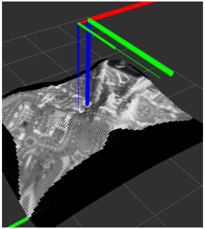
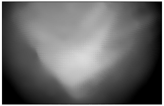
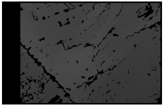
Inhouse dataset results

Mapping

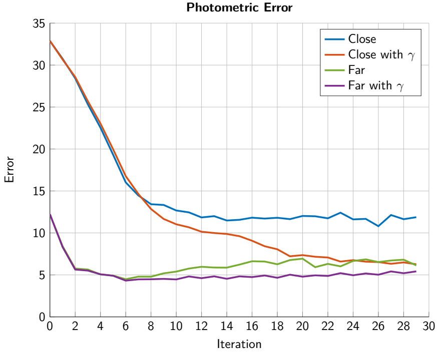
$\beta = 10$
$\gamma = 1e5$

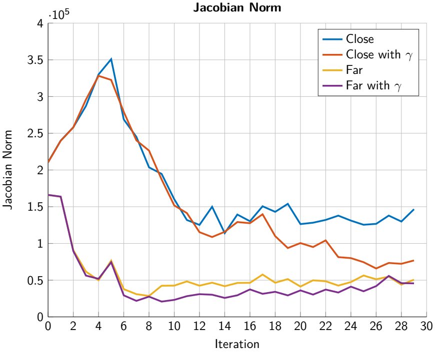





$\beta = 10$
$\gamma = 1e5$

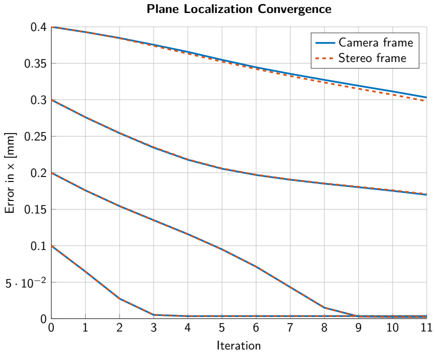





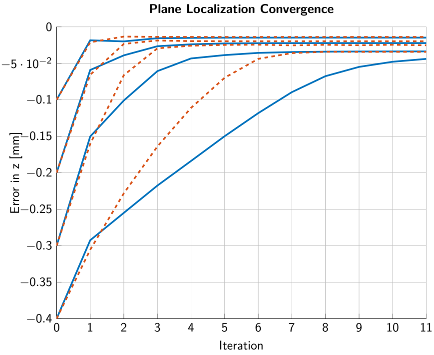
Inhouse dataset convergence
Mapping





Plane Test
Localization





Achievements
Localization

- Created versatile `stereo surface reconstruction` package for
  - variable spline degree and resolution,
  - entirely customizable optimization parameters and
  - rectified and unrectified images.
- Implemented photometric localization algorithm based on one stereo measurement.
- Tested functionalities on real and simulated datasets.

Future Work

Localization

- Implement sequence of mapping and localization steps to improve map accuracy using multiple measurements.
- Integrate new measurements to extend map using bundle adjustment.
- Test framework in realistic sceneries.