ETH
Eidgenössische Technische Hochschule Zürich
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Autonomous Systems Lab
Prof. Roland Siegwart

Semester Thesis

Online Extrinsic Camera Calibration from Multiple Keyframes Using Map Information

Spring Term 2023

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Contents

Preface

...

Abstract

... short summary

Symbols

Symbols

ϕ, θ, ψ	roll, pitch and yaw angle
b	gyroscope bias
Ω_m	3-axis gyroscope measurement
λ	...

Indices

K	Intrinsic parameter matrix
x	x axis
y	y axis
z	z axis
u	horizontal pixel coordinate
u_0	horizontal center pixel
v	vertical pixel coordinate
v_0	vertical center pixel

Acronyms and Abbreviations

ETH	Eidgenössische Technische Hochschule
GPS	Global Positioning System
ICP	Iterative Closest Points algorithm
IMU	Inertial Measurement Unit
OSM	Open Street Map
UTM	Universal Transverse Mercator coordinate system

Chapter 1

Introduction

Obstacle detection is crucial for the safe operation of railway vehicles. A prerequisite for this is knowing where to look for obstacles, which means that tracks ahead of the vehicle need to be correctly identified and located. This could be done by projecting a known railway map into camera view. However, this requires precise knowledge of the camera position and rotation – not typically available in the field or with existing datasets. Given the degree of accuracy required for long-range obstacle detection this is a non-trivial task.

The aim of this semester project is to develop a continuous calibration and reprojection pipeline to estimate the extrinsic parameters of a camera, whose intrinsic parameters are known, given a set of images and associated pose readings from a GPS sensor that is also attached to the vehicle. Moreover, different map data is available, including OpenStreetMap (OSM) data with the positions and properties of railway nodes and tracks, elevation data, as well as a positions of poles that are located next to all railway tracks. The challenge here is to make best possible use of the data combined with visual cues to design an optimisation framework that converges to accurate results.

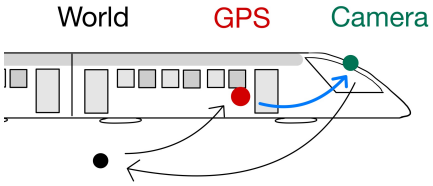
Building upon previous work by Nicolina Spiegelhalter [**?**]

Chapter 2

Background

...

2.1 Coordinate Systems



World: UTM coordinates

GPS

Camera frame

Actual camera frame will change, depending on the orientation of the camera. This is an initial approximation.

2.2 Coordinate Transformations

In order to efficiently transform points between the different coordinate systems, namely those described in the previous section, it is important to understand the underlying methods. This section summarizes the most important concepts.

Table 2.1: Descriptive directions and rotations, with associated GPS and camera axes.

Direction	**Rotation**	**GPS axis**	**Camera axis**
Longitudinal (forward)	Roll	$+X_{GPS}$	$+Z_{cam}$
Lateral (sideways, right)	Pitch	$+Y_{GPS}$	$+X_{cam}$
Vertical (upwards)	Yaw	$+Z_{GPS}$	$-Y_{cam}$

For the purpose of this project, homogeneous transformation matrices have been used most of the time since they are more intuitive. However, quaternions are used for the optimization, where they are dynamically adapted, since they are not prone to numerical singularities.

2.2.1 Homogeneous Transformation Matrix

Transformation, including both translation and rotation, of a vector to point P, from initial frame $\mathcal{A}$ to frame $\mathcal{B}$. This is achieved using the rotation matrix $R_{\mathcal{BA}}$ (notation: frame $\mathcal{A}$ to frame $\mathcal{B}$) and translation vector ${}_{\mathcal{B}}\boldsymbol{t}_{BA}$ (notation: from point A to point B, expressed in frame $\mathcal{B}$). To avoid computation issues, it is crucial to remember which frames the vectors are expressed in.

$$ {}_{\mathcal{B}}\boldsymbol{r}_{BP} = {}_{\mathcal{B}}\,\boldsymbol{t}_{BA} + R_{\mathcal{BA}} \cdot {}_{\mathcal{A}}\,\boldsymbol{r}_{AP} \tag{2.1} $$

This can also be combined as a homogeneous transformation matrix $H_{\mathcal{BA}}$.

$$ \begin{bmatrix} {}_{\mathcal{B}}\boldsymbol{r}_{BP} \\ 1 \end{bmatrix} = \underbrace{\begin{bmatrix} R_{\mathcal{BA}} & {}_{\mathcal{B}}\boldsymbol{t}_{BA} \\ \boldsymbol{0}_{1\times 3} & 1 \end{bmatrix}}_{H_{\mathcal{BA}}} \cdot \begin{bmatrix} {}_{\mathcal{A}}\boldsymbol{r}_{AP} \\ 1 \end{bmatrix} \tag{2.2} $$

To determine the inverse of a homogeneous transformation matrix, the translation vector need not only be reversed but also rotated to the new frame, while the rotation matrix is simply transposed.

$$ H_{\mathcal{AB}} = \begin{bmatrix} R_{\mathcal{AB}} & {}_{\mathcal{A}}\boldsymbol{t}_{AB} \\ \boldsymbol{0}_{1\times 3} & 1 \end{bmatrix} = \begin{bmatrix} R_{\mathcal{BA}}^{T} & -R_{\mathcal{BA}}^{T} \cdot {}_{\mathcal{B}}\,\boldsymbol{t}_{BA} \\ \boldsymbol{0}_{1\times 3} & 1 \end{bmatrix} \tag{2.3} $$

2.2.2 Quaternion Rotation

Definition of a quaternion $\boldsymbol{q}$ (4D vector) and its conjugate $\boldsymbol{q}^{*}$.

$$ \boldsymbol{q} = q_w + q_x \cdot \boldsymbol{i} + q_y \cdot \boldsymbol{j} + q_z \cdot \boldsymbol{k} = \begin{bmatrix} q_w \\ q_x \\ q_y \\ q_z \end{bmatrix} \qquad \boldsymbol{q}^{*} = \begin{bmatrix} q_w \\ -q_x \\ -q_y \\ -q_z \end{bmatrix} \tag{2.4} $$

Must be a unit quaternion (scaled to unit norm)
Rotation using the quaternion product $\otimes$ (equal to cross-product minus dot-product)

$$ \begin{bmatrix} 0 \\ {}_{\mathcal{B}}\boldsymbol{r} \end{bmatrix} = \boldsymbol{q}_{\mathcal{BA}} \otimes \begin{bmatrix} 0 \\ {}_{\mathcal{A}}\boldsymbol{r} \end{bmatrix} \otimes \boldsymbol{q}_{\mathcal{BA}}^{*} \tag{2.5} $$

2.3 Camera Reprojection & Image Undistortion

2.3.1 Reprojection via the Pinhole Camera Model

Reprojection of coordinates (x, y, z) in the camera frame to pixel coordinates (u, v) in the image plane. The variables f_x and f_y are the focal lengths in pixels, while c_x and c_y are the principal point coordinates in pixels.

$$ u = f_x \cdot \left(\frac{x}{z}\right) + c_x \tag{2.6} $$

$$ v = f_y \cdot \left(\frac{y}{z}\right) + c_y \tag{2.7} $$

This can also be written in matrix form, with the camera instrinsics matrix K, where the variable λ is the depth scaling factor since infinitely many 3D points would project to the same 2D point.

$$\lambda \begin{bmatrix} u \\ v \\ 1 \end{bmatrix} = \underbrace{\begin{bmatrix} f_x & 0 & c_x \\ 0 & f_y & c_y \\ 0 & 0 & 1 \end{bmatrix}}_{K} \cdot \begin{bmatrix} x \\ y \\ z \end{bmatrix} \tag{2.8}$$

2.3.2 Image Undistortion: Equidistant Model

$$r = \sqrt{u^2 + v^2} \tag{2.9}$$

$$\theta = \arctan(r) \tag{2.10}$$

$$\theta_d = \theta(1 + k_1 \cdot \theta^2 + k_2 \cdot \theta^4 + k_3 \cdot \theta^6 + k_4 \cdot \theta^8) \tag{2.11}$$

...
Done using OpenCV fisheye

2.4 Iterative Closest Points (ICP)

Optimization

Chapter 3

Method

This chapter outlines the approach taken ...

Summary of steps / diagram

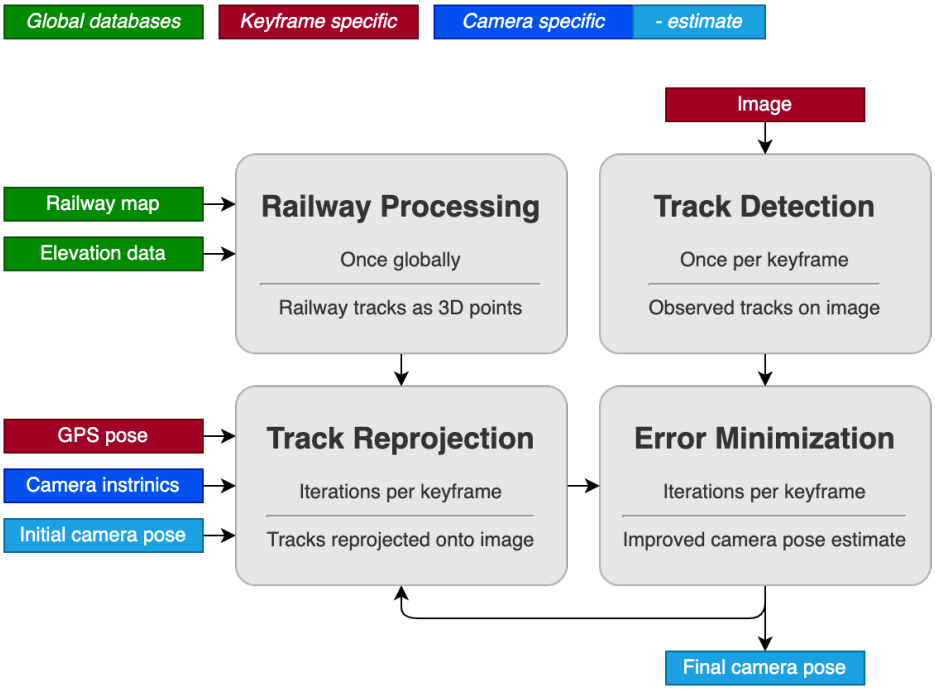


Figure 3.1: Overview of main components, their interactions, and inputs/outputs.

3.1 Railway Processing

At first, the nodes and tracks from the OSM file are converted into the data that is actually needed: 3D points of the railway tracks that are regularly spaced, a property that the OSM file does not fulfil.
Process list / pseudo-code / diagram

1. Read OSM file
2. Extract nodes and tracks
3. Interpolate density of nodes
4. ...
5. Add elevation data to get 3D points

3.2 Track Reprojection

3.3 Track Detection

3.3.1 Railway Tracks

3.3.2 Poles

3.4 Error Minimization

Chapter 4

Implementation

Objects, classes & interactions
Algorithmic implementation, efficiency, speed
Flowchart of code (files, classes, methods)
Better as table ???
Using Python for most tasks
C++ for optimization with Ceres
Libraries: OpenCV, NumPy, Ceres, ...

4.1 Python Classes & Objects (Methods, Data)

... main file & sequence

4.1.1 Railway

Which mehods & data types enable the process as described in method

4.1.2 Keyframe & GPS

Image, annotations

4.1.3 Camera

4.1.4 Transformation

4.2 C++ Optimization: Ceres Solver

4.2.1 Cost Function

4.2.2 Residuals

4.2.3 Parameters

Chapter 5

Results

...

5.1 Evaluation

Chapter 6

Conclusion

...
Quality of results, accuracy, ...
Robustness, ...
Extensions, future work, ...

Bibliography