# Calibration Setup for Stereo DVS

eingereichtes
Projektpraktikum
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P R A C T I C A L  C O U R S E

# Calibration Setup for Stereo DVS

Problem description:

In our lab, we use so called dynamic vision sensors[1]. The working principle of these recently invented sensors is very different from the one of conventional cameras and mimics the functionality of biological eyes. We want to make use of the advantages of the DVS in a stereo setup, i.e. extract depth from the vision fields of two parallel DVS like the brain does with your eyes. But while the brain knows the exact orientation of your eyes towards each other, in a machine vision setup, the precise orientation of the vision sensors is not known. In this project, we would like you to develop a system for the calibration of two DVS, i.e. identifying the geometrical and intrinsic camera parameters, as well as rectifying distortion of the optical lenses. You will need to build a setup consisting of blinking LEDs with very precisely known positions in space and develop a method to automatically extract the parameter values from the vision stream of two DVS.

Tasks:

- Get familiar with dynamic vision sensors and multi-camera geometry
- Design a system for measuring the intrinsic camera parameters and geometry of a stereo setup
- Rectify lens distortion
- Evaluate the quality of calibration and rectification

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Bibliography:

[1] Lichtsteiner, P., Posch, C. and Delbruck, T. *A 128 times; 128 120 dB 15 us Latency Asynchronous Temporal Contrast Vision Sensor* IEEE Journal of Solid-State Circuits Feb. 2008 p. 566-576

# Documentation / Report

Part of this project was contributed within the scope of a practical course at the TUM NST. This document is the final project report.

The following sections will give a precise overview of the project goal, problems and insights which we gained while developing a solution.

## Table of Contents



## Project Summary

### Project Goal

In order to extract depth information from a stereo camera setup, most methods require some

information about their positioning towards each other. The geometrical and intrinsic camera parameters as well as the rectification matrix are necessary to calculate world coordinates from image features. A number of tools and a lot of literature on this topic exists and is in widespread use the research community and industry. The calibration procedure for conventional cameras is highly standardized.
Dynamic Vision Sensors are a promising new type of sensor that works with events instead of frames. Like traditional cameras, the mounted lens needs to be calibrated to achieve exact depth information. However, because of the difference in information representation between the two kinds of sensors, conventional calibration procedures like checkerboard corner detection cannot be applied. This research project aims to develop a method that facilitates extracting the parameters from a vision stream of a stereo eDVS camera setup.

# Initial Plan

In the beginning of the project, the core thought of our plan was the following: Get as fast as possible to a working calibration setup and then iterate on this initial setup. Therefore, we have chosen to use existing software and methods to calibrate a camera. In details, the road map included:

- Plum Bob camera model (as in OpenCV library): Simplest method, which is in use for normal cameras with usual lenses (not fish-eye lenses) and should therefore also work for an eDVS
- Assumption of one planar stereo pair with overlapping field of view as it is the most common setup and simplifies the calibration method
- Implement eDVS driver for ROS in order to profit from existing image processing tools and to run stand alone (open source and e.g. without Matlab)
- Use available user interface of ROS (ros rqt) to make calibration run more user friendly
- Use existing LED board for calibration: Provides wider viewing angles and better frequency tracking than an animated image displayed on a computer monitor.
- Benchmark mathematical model using reprojection
- Benchmark stereo setup using ground-truth data and a calibration rig

# Key Challenges

The issues in our project confirmed our approach to focus on a simple working calibration setup in the beginning. A summary of the main obstacles are listed below:

- **eDVS Driver**:
  - The available protocol of the event stream does not provide a reliable method to find the beginning of packets. Especially the "E1" type, which we used at first, often lead to wrong packet beginnings and therefore corrupted data.
  - The hardware supports to set biases. But even with the help of our supervisors, we could not implement a working version. The camera freezes as soon as biases are read or changed.
  - Under-documented protocol, rough or not available drivers made our own modifications necessary and error prone.
- **LED Board**:
  - Reflections at the corner of the LED board had negative influence on the pattern detection.
  - The original software of the board did not fit our purpose: Several different blinking

frequencies and too many blinking LEDs at once (80) made detection overly complicated or even impossible.
    - Movements of the board or cameras during the calibration process introduced blur over time.
    - Missing documentation of the LED board firmware made changes very challenging and time consuming.
- **Pattern detection issues**:
    - The key challenge was to reliably detect the LED pattern in the event stream. Many factors, like movements, too many LED points, reflections, dark light, noise, limited optics and low sensor resolution made this task very complicated to master.
    - Even with a more reliable detection method, sometimes the patterns are spurious or even wrong. Consequentially, we introduced an optional manual step to exclude wrong patterns from the calibration step.
- **Varying intrinsic camera parameters**: The sometimes substantial differences in the intrinsic parameters of two cameras lead to problems in the stereo rectification: It impeded to correctly identify a plausible rectification matrix. Therefore, the 3D reconstruction is sometimes very challenging.

## Summary of Results

Our proposed method does successfully calibrate, undistort and rectify mono or stereo setups.

In our evaluation, we found that quality issues persists: A repeated calibration of one camera using the same setup led to varying intrinsic camera parameters. Especially the focal length and the principal point of view varied more than 15%.

## Future Work

We achieved all of the project goals. Still, there are many areas to improve our presented solution. We propose two main points:

- **Repeatable identification of intrinsic camera parameters**: Investigate main influence on varying performance and results (e.g. limitations of camera model, noisy data)
- **Provide additional calibration guidance**: As an example, add an assistant, which guides the user through the calibration process (e.g. connect cameras, automatically estimate quality of available patterns).

# What is an eDVS?

An eDVS (embedded Dynamic Vision Sensor) produces an event stream. Compared to a usual frame-based camera, the eDVS produces an event every time a pixel changes. This key difference enables for example very fast feedback cycles (<5ms). The used so-called silicon retina chips are developed by the The Institute of Neuroinformatics Zürich, which also provides further information. In our project we used the miniaturized eDVS.

# Software Setup

## Existing Software as Starting Point

Camera calibration and rectification is already done routinely for "normal", frame-based cameras. Therefore, there exist many tools to tackle the task. One of them is the open-source computer vision library OpenCV. Based on this library, the open source Robot Operating System (ROS) provides a package, called Camera Calibration. It helps to facilitate the calibration process of „monocular or stereo cameras using a checkerboard calibration target“ [1]. Unfortunately, it is only for frame-based cameras. For that reason, the Robotics and Perception Group of Zurich published another open-source package for ROS called rpg_dvs_ros. The software tries to use existing parts of the camera_calibration package and OpenCV again.

Instead of trying to reinvent the wheel again, we think the best approach is to build upon proven existing software. Therefore, this project uses the rpg_dvs_ros package as starting point. We forked the original repository in order to implement and add our new features.

## eDVS Driver for ROS

The rpg_dvs_ros package (DVS_ROS) expects a rostopic input stream of the format `dvs::EventArray` . The eDVS on the other hand provides the event stream using its own custom protocol. The used communication channel is an emulated serial device over UART. Further details provides the IniLabs eDVS guide as well as the Silicon Retina Wiki of the INI Zurich. After connecting the eDVS camera over USB to a Linux computer, an emulated serial device usually called `/dev/ttyUSB0` will be created (since udev 2.5, you can also access a device using its persistent name `/dev/serial/by-id/usb-FTDI_Dual_RS232-HS-if00-port0` ). Using the console, one can send and receive commands on the interface, for example as illustrated below:

```
#set interface speed to 4Mbit, no IO processing (--> no EOF)
$ stty -F /dev/ttyUSB0 4000000 raw

#start background process to see camera output
$ cat /dev/ttyUSB0 &

#send reset command to the camera
$ echo 'R' > /dev/ttyUSB0

#set event mode to 1 and start sending events
$ echo -ne '!E1\nE+\n' > /dev/ttyUSB0

#display help of available commands
$ echo '??' > /dev/ttyUSB0

#answer could be:
EDVS128_LPC2106, V2.2: Apr 22 2015, 17:16:20  (TIMESYNC)
System Clock: 64MHz / 1us event time resolution
Supported Commands:
 E+/-       - enable/disable event sending
 !Ex        - specify event data format, ??E to list options
 !ET[=x]    - set/reset the event timestamp
 !ET[M0,M+] - active synchronized time master mode; 0:stop, +:run
 !ETS       - active synchronized time slave mode
 !Bx=y      - set bias register x[0..11] to value y[0..0xFFFFFF]
 !BF        - send bias settings to DVS
```

```
 !BDx       - select and flush default bias set (default: set 0)
 ?Bx        - get bias register x current value
 0,1,2      - LED off/on/blinking
 !S=x       - set baudrate to x
 !S[0,1,2]  - UART echo mode (none, cmd-reply, all)
 R          - reset board
 P          - enter reprogramming mode
 ??         - display help
??E
 !E0   - 2 bytes per event binary 0yyyyyyy.pxxxxxxx (default)
 !E1   - 1..3 bytes timestamp (7bits each), time difference (1us resolution)
 !E2   - 4 bytes per event (as above followed by 16bit timestamp 1us res)
 !E3   - 5 bytes per event (as above followed by 24bit timestamp 1us res)
 !E4   - 6 bytes per event (as above followed by 32bit timestamp 1us res)
```

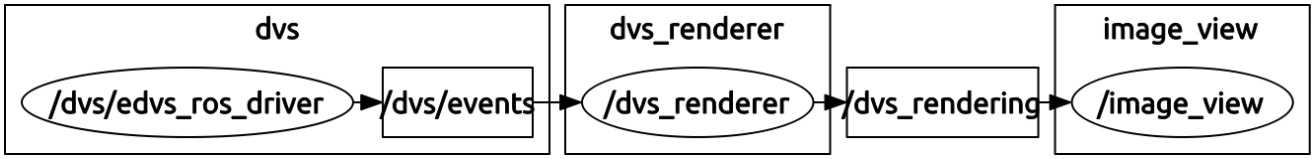
> **Note** When sending multiple commands in one echo, e.g. `$ echo -ne 'R\n!S2\n!E1\nE+\n' > /dev/ttyUSB0` , the eDVS microcontroller might behave unexpected. We experienced some issues like the camera not starting to send data.

The eDVS driver for ROS is based on an EDVS.h file from NST TUM. Our newly developed `edvs_ros_driver` package uses `EDVS.h` to exchange data with the hardware. It's main purpose is the setup and integration, mainly

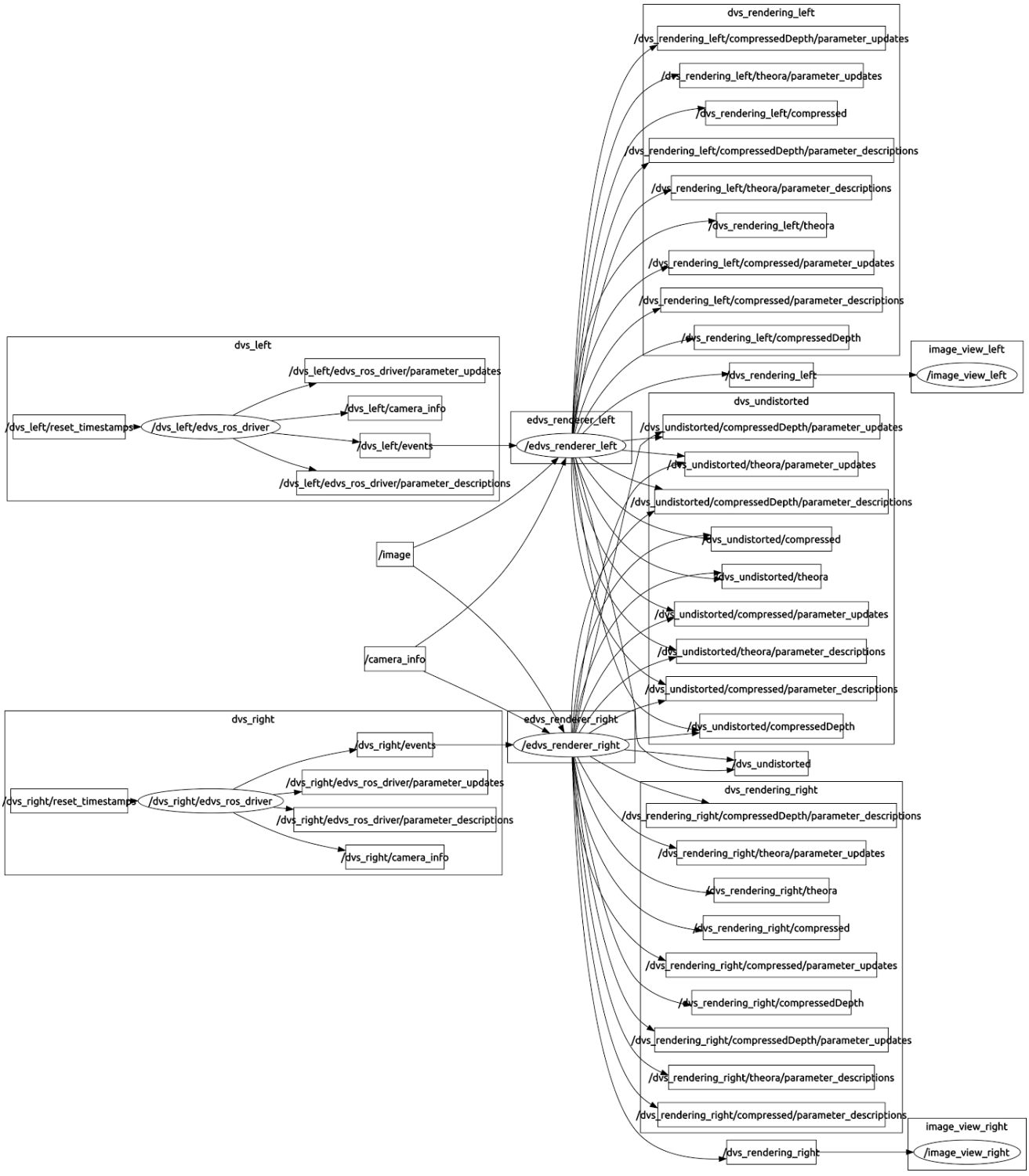
- reset eDVS and set proper event format
- set master and slave for time synchronization in stereo setup mode
- reset timestamps on sensors
- provide sensor information, e.g. resolution.

## Computation Graph of Software Nodes

The basic flow of data from the eDVS hardware driver through the DVS renderer to an image_view, displayed with using the rosgraph tool:




Basic flow in the calibrated stereo case:




Computation graph during stereo calibration with activated pattern picker tool:


# Calibration Model

The basis of the model is a so-called pinhole camera model. The calibration uses an extended version, the Plumb Bob distortion model, which is a sufficient and simple model of radial and tangential distortion.

The intrinsic camera matrix is the standard 3x3 matrix containing focal lengths (fx, fy) and principal point(cx, cy).

In the stereo case, the calibration also provides rectification and projection matrices.

The rectification matrix is the rotation matrix that aligns the camera coordinate systems to the ideal stereo image plane so that epipolar lines are parallel.

The projection matrix is the 3x4 stereo extension of the intrinsic matrix. It adds the position of the second camera's optical center in the first camera's image frame.

You can read the full specs in the CameraInfo ROS message documentation.

Given a 3D point [X Y Z]', the projection (x, y) of the point onto the rectified image is given by:

$$\begin{bmatrix} u \\ v \\ w \end{bmatrix} = P \begin{bmatrix} X \\ Y \\ Z \\ 1 \end{bmatrix}$$

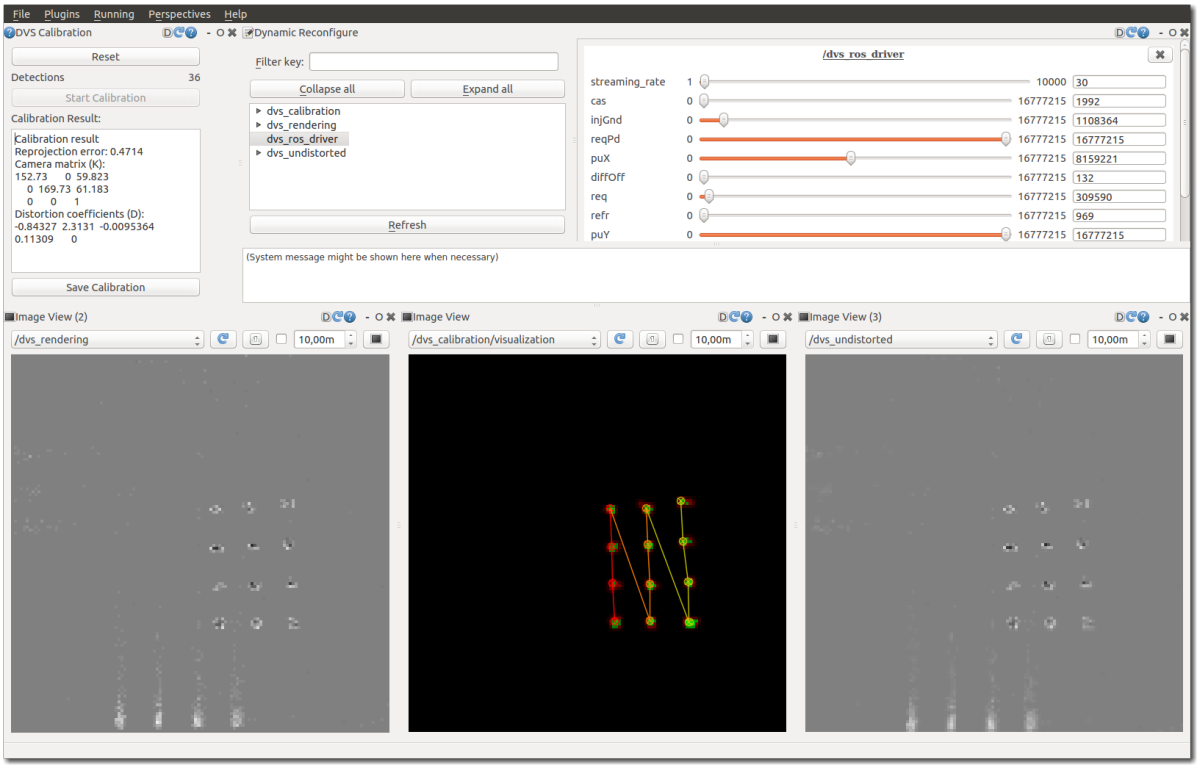
$$x = u/w$$

$$y = v/w$$

# Calibration Walkthrough

1. Setup
    - Set up your software environment. The process is explained in detail in the Installation section of the reposistory's README.md.
        - Install necessary prerequisites (ROS, catkin_simple, libcaer, libusb-1.0-0-dev)
        - Check out this repository
        - Build it.
    - Set up your LED board.
        - We provide some documentation and the firmware for our board at our ledboard repository.
        - If you want to follow our recommendation to use the fixed calibration rig, mount eDVS cameras and LED board on it.
        - Connect cameras to computer and verify access rights with `$ echo R > /dev/ttyUSB0` (logging out and in might help)
2. Calibrate in mono mode to find intrinsic parameters of the first camera.
    - Bring up the *mono* calibration GUI: `$ roslaunch dvs_calibration intrinsic_edvs.launch`
        - Make sure the camera image rendering (bottom left) looks good
        - All LED blobs are visible
        - No or very little reflection
        - X/Y is correct for both on and off (workaround)
    - See if the LED pattern recognition (visualization at bottom center) works
        - LEDs blinking with correct frequency show up as green dots (adjust blink time and tolerance)
        - LED blob borders and reflections are red (adjust threshold)
        - Recognized pattern is drawn over led blobs (adjust pattern width/height)
    - Record calibration pattern data
        - Start fresh by pressing the /Reset/ button in top left panel (might need to resize window)
        - Successful pattern recognitions increment counter in top left
        - Don't move too much
        - Try to capture enough patterns close to image edges, because lens distortion increases radially. Check "Capture Images" at MathWorks's single camera calibration documentation.
        - Capture something like 40 patterns
    - Calculate and save intrinsic calibration
        - Hit the *Start Calibration* button to start calculations (this freezes rqt).
        - If the parameters seem OK, you can save them. The path will be `~/.ros/camera_info/eDVS128-_dev_ttyUSB0.yaml` (if your camera is on /dev/ttyUSB0).
        - Inspect the undistortion result quality in the lower right image view. (example)
        - You could also use a Matlab script to visualize distortion in a quiver plot.
    - Repeat for the second camera (use `$ roslaunch dvs_calibration intrinsic_edvs_usb1.launch` )

Screenshot of mono calibration:




- Calibrate in stereo mode
  - Make sure you have intrinsic parameters for the left and right camera in `~/.ros/camera_info/eDVS128-_dev_ttyUSB0.yaml` and `~/.ros/camera_info/eDVS128-_dev_ttyUSB1.yaml` , respectively.
  - Start the stereo calibration GUI: `$ roslaunch dvs_calibration stereo_edvs.launch`
  - Record patterns as you did in mono mode (Patterns are stored if they appear in both cameras simultaneously)
  - *Start Calibration* and *Save Calibration* (The .yaml files will be overwritten)

# Using the Calibration Data

## In ROS

If camera calibration has been completed beforehand, it is easy and straightforward to use the calibration in ROS. First, make sure the precomputed calibration files are where ROS's camera_info_manager expects them. This is usually `~/.ros/camera_info/eDVS128-_dev_ttyUSB0.yaml` . The camera_info_manager ROS package, which is part of ROS's image_pipeline stack, will then be able to use the calibration automatically.
The image_pipeline is designed to process complete frames of pixel-images. Thus, we need the *dvs_renderer* to generate an image from an accumulation of eDVS events.

Usage:

- Start eDVS event output: `$ roslaunch edvs_ros_driver edvs-stereo.launch`
- Render images and display stages of image_pipelines stereo processing: `$ roslaunch edvs_ros_driver stereo-display.launch`

## Elsewhere

The calibration data can easily be used in other environments. The following example generates a Matlab cameraParameters object:

```
cp = cameraParameters( ...
    'IntrinsicMatrix', [164.0138, 0, 80.1241; 0, 164.8755, 44.2025; 0, 0, 1], ...
    'RadialDistortion', [-0.2875, 0.1980], ...
    'TangentialDistortion', [-0.0038, 0.0081]);
```

## Calibration Tweaks

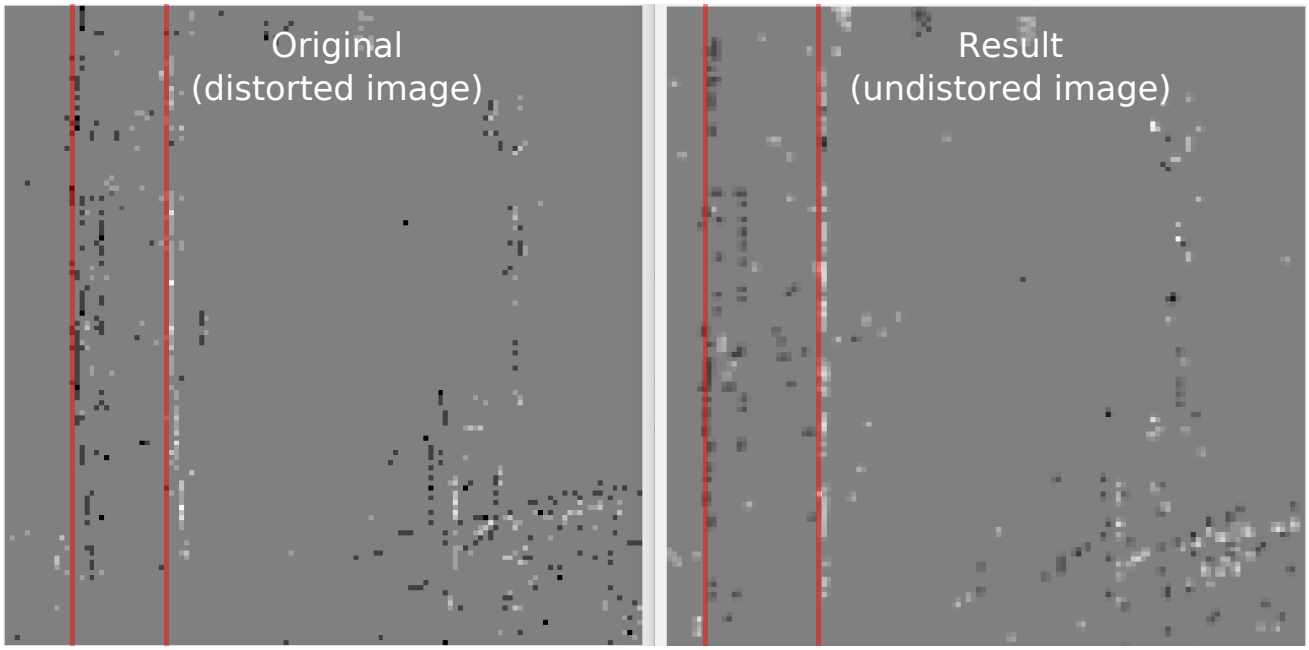
See Calibration Details and Parameters.

- Use the tool that displays last detection
- Use the tool that asks for approval every time a pattern is detected

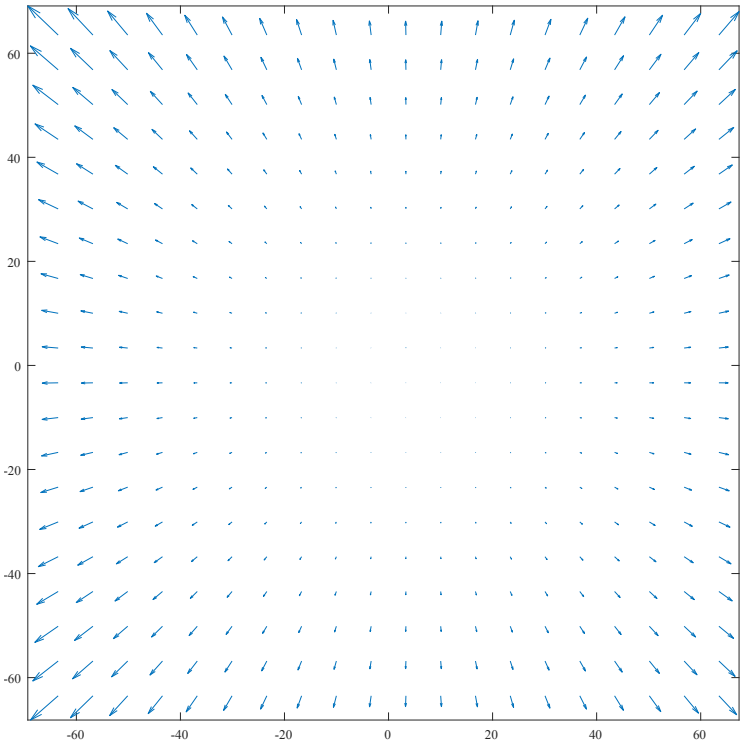
# Results

## Intrinsic and Extrinsic Camera Parameters

Example of an original image vs. undistorted image:

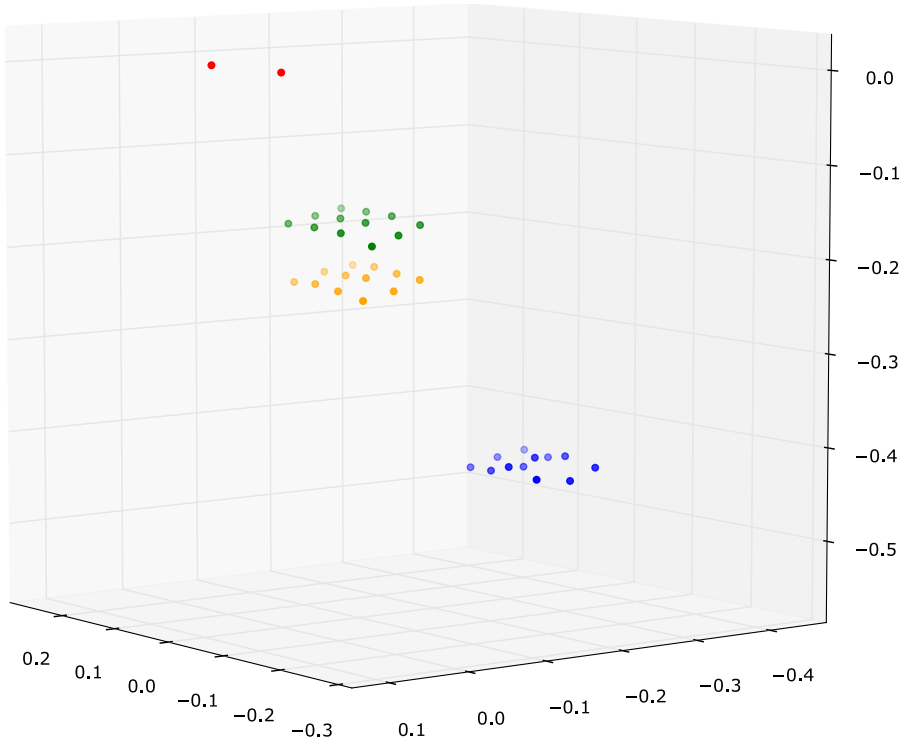



Visualization of eDVS lens distortion using our Matlab script.




# 3D Reconstruction

With successful pattern capture capabilities, 3D point reconstruction can be attempted. The plot below shows the camera positions as detected during calibration in red. Three 3x4 LED board patterns in different distances are visualized in green, orange and blue. The plot was created with a Python script.




# Benchmark

## Mathematical Model Benchmark

After a model is calculated, one can check, how good the model fits with the provided LED points. The used LED points will be projected to the world model and then reprojected from the model to the

image. The euclidean distance of the real input image point and the reprojected point will be used to as error. The reprojection error provided after the calibration is the root mean square over all these errors. For example, an reprojection error of 3.0 would indicate, that, on average, each projected point is 3px away from the original point.

> **Where can I find the reprojection error in the interface?** The value is displayed in a text field in the calibration interface, after the calibration has successfully finished.

A small reprojection error does not imply a good world model. It can only describe, how good the provided calibration points can fit into one common model. Therefore, a lot of more points might even increase this error, as every new point can add noise.

### Benchmark using Ground Truth

One goal was to create an benchmark for the calibration and rectification result. Our requirements were to be reproducible and easy to perform. It should provide ground truth and according calculated depth data. This enables to calculate the 3D reprojection error.

One approach to providing ground truth is using an marker based infrared optical tracking system. While such a system is available at the NST chair, the anticipated time for setting up and understanding the system did not seem to be worthwhile given the introduced spatial noise in ground truth and increased complexity of the experimental setup.

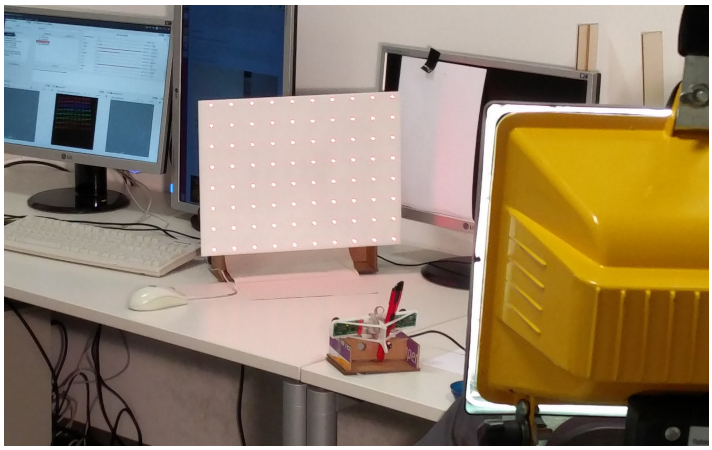
Instead, we propose to use a laser-cut high density fiberboard construction to reproducibly and accurately move the LED board. The eDVS stereo setup is mounted on the construction. The board moves on a Z-axis rail, where it snaps in at fixed positions. When both eDVS sensors capture the same feature (e.g. the blinking pattern), we can triangulate the feature's 3D positions with the help of the prerecorded camera calibration data being evaluated. The distance (delta) we can calculate between these 3D positions is compared to the Ground-truth distances which can easily measured or deduced from the rig's design files.
Using this method guarantees that the ground-truth data is the same for every run, even when the mounting position of the eDVS varies in the order of some millimeters.

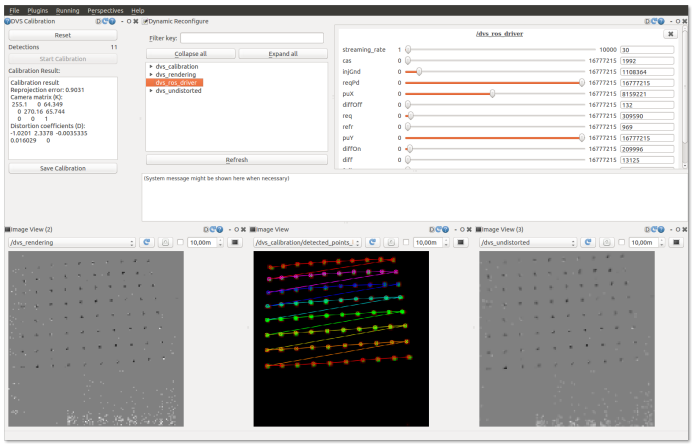
## Learnings

### LED Board with too many blinking LEDs

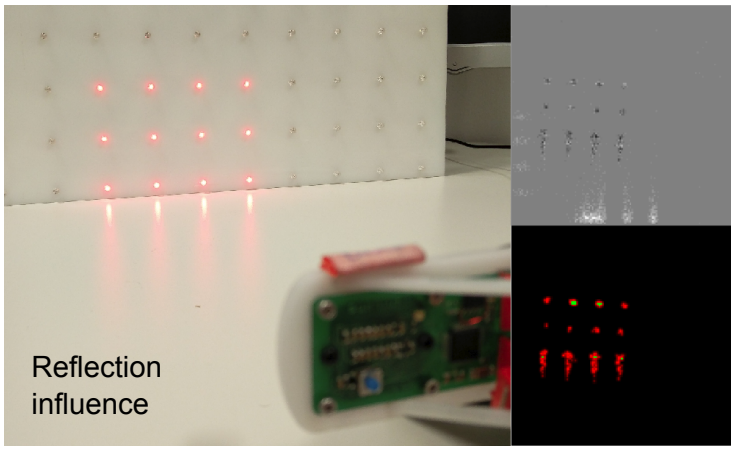
At the beginning we experimented with an LED board with 80 LEDs (200Hz), which produced too many events. We discovered, that the eDVS can not cope with so many events (even at 4MBit data rate). On the other hand, the DVS (not eDVS) has no problem with that many events. In our experience the DVS usually reports about five times as many events from the same scene.

With a lot of additional light (to surpress noise) and 10.0s transition map aggregation time, even the full board could be detected in the end. The big number of points makes the calculation of the principal point more accurate. However it is very difficult to get all LEDs to be detected without too much noise.





## Reflection from LED Board

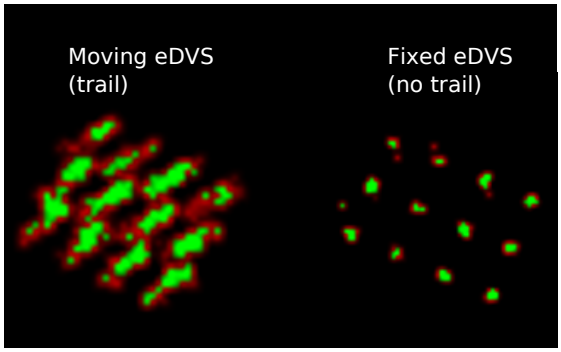



LEDs near to the border of the board reflected too strongly, which had a negative influence on pattern detection. We experimented with some textile to absorb the reflections. The result was surprisingly good. Yet, for our final solution, we disable the LEDs at the border to achieve the same detection quality without depending on covers.

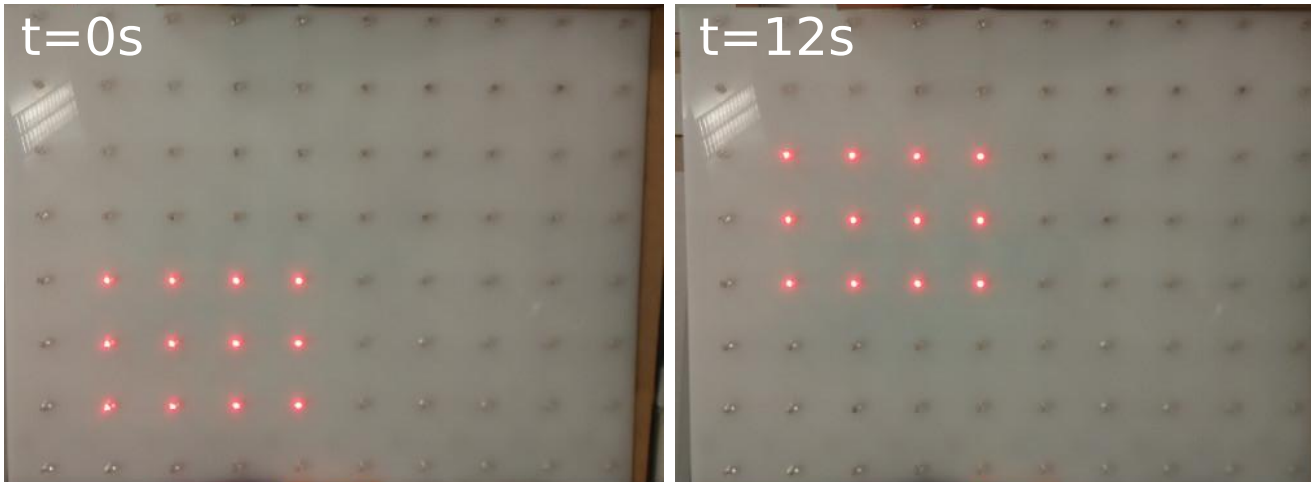
## Movements during Calibration Process

Our first calibration experiments used one of the following setups: (1) The eDVS was moved around to produce events of a fixed LED board from different point of views. (2) The eDVS was fixed, while the LED board was moved around in its field of view. Both approaches resulted in some issues: The sub pixel accuracy calculation of the LED's center was disturbed by the moving scene. This is because the sensor does not produce frames, but a constant stream of events. The transition map of the events accumulated during one time frame hence included a visible trail of LED point movements, as illustrated in the figure below. The time frame (and thus led trail length) can not be decreased, or

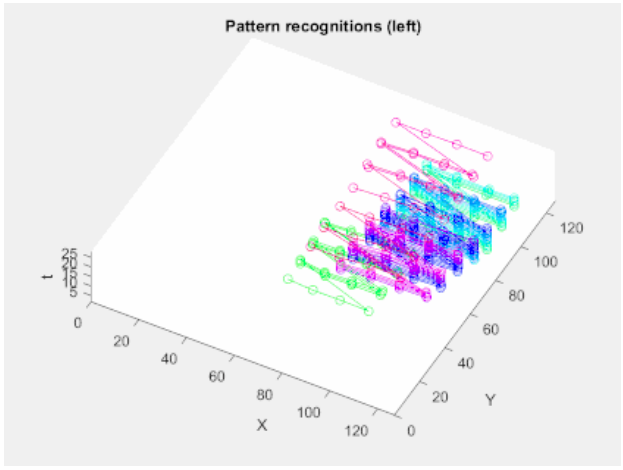
noise will prevent pattern detection. Therefore the estimation of the LED blob's center position is not exact. This lead to suboptimal calibration results.




Our solution is to use both (1) a statically mounted camera and (2) a fixed led board. As both parts are physically not moving, we prevent the influence of pixel trails and achieve better results. In order to collect image points of blinking LEDs over the whole sensor area, the board's software incrementally shifts the illumination pattern every 10 seconds. The following picture shows the board at the beginning and after some seconds.




In our animation of pattern recognition you can observe how (1) the pattern shifts over the board and (2) how pixel coordinates of the same pattern points vary relatively little (about +- 0.3px max), because no movement is introduced.




## Wrong Buffering rejects Events

The buffer in the original `eDVS.h` read all available bytes on the serial interface. Sometimes, the buffer

ended in the middle of an event package. Then, it rejected the package, because it was incomplete. Our solution was to always read at least six bytes from the serial before we try to process it.

### Original eDVS.h without Timestamps

The original `eDVS.h` did not provide timestamps. Hence, we implemented this functionality ourselves. As we learned later, there is an improved version available at edvstools.

### Shifted X and Y Coordinates for On-Events

Sometimes the sensor image shows shifted x and y values for on-events. The reason so far is not completely clear. We used the following quick-fix (while the calibration interface was running) in a separate terminal:

```
#press hardware reset button on eDVS

#send reset command
$ echo -ne 'R\n!' > /dev/ttyUSB0

#sometimes send reset event again, if it was not working
#(you can check if the calibration interface still shows an image)
#after the rest, it should not show any events anymore
$ echo -ne 'R\n!' > /dev/ttyUSB0

#set event mode to 1 and start sending events again
$ echo -ne '!E1\nE+\n' > /dev/ttyUSB0
#now your events should be displayed correctly
```

Later, we switched to the "E2" timestamp format and used a Boost circular buffer for processing. This ensured that no events were split and lost. This also removed the sporadic x/y shifts and mysterious noise at image borders (it seems that a few timestamp bytes were interpreted as X or Y some time).

# Suggested Improvements for eDVS Ros Driver

There already exists an improved version of the basic EDVS.h file, which was the starting point for the ROS driver. This early EDVS.h is very limited in functionality. Further efforts regarding the eDVS calibration topic should consider switching to the most recent version of the library (edvstools).

# Tools

## Store Detected Patterns

In order to analyze, which points where detected, one can record the result from e.g. these topics:

- /dvs_calibration/detected_points_left_or_single
- /dvs_calibration/detected_points_left_or_single_pattern

Here a short example, how to e.g. record and view the data:

```
#first source resources
source devel/setup.bash

#run the calibration interface
roslaunch dvs_calibration intrinsic_edvs.launch

#now, on e.g. other terminal
#this will display only the transition maps with detected points
rosrun                              image_view                                  image_view
image:=/dvs_calibration/detected_points_left_or_single_pattern &

#this will show the detected points messages
rostopic echo /dvs_calibration/detected_points_left_or_single &

#this will record both of them in a file
rosbag          record          /dvs_calibration/detected_points_left_or_single_pattern
/dvs_calibration/detected_points_left_or_single
```

# Playback Stored Patterns

For playback of the recorded data, run:

```
roscore &

#this will show the detected points messages
rostopic echo /dvs_calibration/detected_points_left_or_single &

#play in an endless loop the file
rosbag play -l 2015-12-14-15-17-38.bag

#or step through the file: press p in the command window or
#space to pause playback
#rosbag play --pause 2015-12-14-15-17-38.bag
```

# Plot Patterns with Matplotlib

first, convert rosbag file to csv

```
rostopic  echo  -b  2015-12-22-00-53-33.bag  -p  /dvs_right/out/image_object_points  >
stereo-right.csv
rostopic  echo  -b  2015-12-22-00-53-33.bag  -p  /dvs_left/out/image_object_points  >
stereo-left.csv
```

then, plot it using a small python script

```
python utils/plot.py stereo-right.csv
#or try two or more files at once
python utils/plot.py stereo-right.csv stereo-left.csv
```

for 3d recordings, you can also use

```
python   utils/plot3d.py   ../ttyUSB0.yaml   ../ttyUSB1.yaml   points-left.csv   points-
```

```
right.csv

#or, if like usually, yaml with calibration info is stored in home file
python           utils/plot3d.py           ~/.ros/camera_info/eDVS128-_dev_ttyUSB0.yaml
~/.ros/camera_info/eDVS128-_dev_ttyUSB1.yaml points-left.csv points-right.csv
```

We hereby certify that this advanced seminar has been composed by ourselves, and describes our own work, unless otherwise acknowledged in the text. All references and verbatim extracts have been quoted, and all sources of information have been specifically acknowledged.